Hearing Research xxx (2018) 1–17

Contents lists available at ScienceDirect

Hearing Research

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

Review Article

Psychophysiological measurement of affective responses during speech perception

Alexander L. Francis*, Jordan Oliver

Department of Speech, Language and Hearing Sciences, Purdue University, Lyles-Porter Hall, 715 Clinic Dr., West Lafayette, IN 47907, USA

ARTICLE INFO

Article history:
Received 31 October 2017
Received in revised form
2 July 2018
Accepted 13 July 2018
Available online xxx

Keywords:
Listening effort
Affect
Emotion
Autonomic nervous system
Psychophysiology
Speech in noise

ABSTRACT

When people make decisions about listening, such as whether to continue attending to a particular conversation or whether to wear their hearing aids to a particular restaurant, they do so on the basis of more than just their estimated performance. Recent research has highlighted the vital role of more subjective qualities such as effort, motivation, and fatigue. Here, we argue that the importance of these factors is largely mediated by a listener's emotional response to the listening challenge, and suggest that emotional responses to communication challenges may provide a crucial link between day-to-day communication stress and long-term health. We start by introducing some basic concepts from the study of emotion and affect. We then develop a conceptual framework to guide future research on this topic through examination of a variety of autonomic and peripheral physiological responses that have been employed to investigate both cognitive and affective phenomena related to challenging communication. We conclude by suggesting the need for further investigation of the links between communication difficulties, emotional response, and long-term health, and make some recommendations intended to guide future research on affective psychophysiology in speech communication.

Contents

---

* Corresponding author.
E-mail addresses: francisa@purdue.edu (A.L. Francis), oliver49@purdue.edu (J. Oliver).

https://doi.org/10.1016/j.heares.2018.07.007
0378-5955/

Please cite this article in press as: Francis, A.L., Oliver, J., Psychophysiological measurement of affective responses during speech perception, Hearing Research (2018), https://doi.org/10.1016/j.heares.2018.07.007

1. Introduction

Why do some people tune out of a conversation they find difficult to understand? Why do some people with hearing impairment avoid noisy social situations they used to enjoy? Why do some people who have spent thousands of dollars on hearing aids stop wearing them entirely? Why do some people who work or play in noisy environments choose not to wear hearing protection? In these cases, individuals are making decisions that immediately or eventually limit their ability to communicate effectively, potentially damaging their auditory health and/or psychosocial well-being. Certainly, in some cases people may simply be unaware of the full magnitude of the risk, but in general such decisions are based on some estimation that the relative benefit of taking a particular action is not worth whatever cost it imposes. When considering why people make decisions about communication, whether these are short-term decisions like whether to continue attending to a particular conversation, or long-term decisions like whether to stop wearing hearing aids, hearing researchers have begun to consider not only the individual's *ability* to communicate effectively in a particular context, but also the *effort* required (either the actually exerted effort or the demanded effort) (McGarrigle et al., 2014; Pichora-Fuller et al., 2016; Kramer et al., 2016; Mackersie and Calderon-Moultrie, 2016; Eckert et al., 2016; Koelewijn et al., 2014; Winn, 2016; Kuchinsky et al., 2013; Zekveld et al., 2011), and the *motivation* to pursue each of the available options (Picou and Ricketts, 2014; Richter, 2016). Here, we argue that the contribution to communication decisions of cognitive factors such as effort and motivation is largely mediated by their effect on the listener's immediate emotional state (Bandyopadhyay et al., 2013; Baumeister et al., 2007; Bechara, 2004; Matthen, 2016). Therefore, understanding how and why listeners make specific communicative decisions also requires understanding their emotional or affective response to communication demands. In this review, we present an overview of some common psychophysiological methods that may be useful in research on affective responses, and discuss some important theoretical concerns related to their employment.

In the long run, we believe that psychophysiological research on affective responses to listening challenges will contribute to a better theoretical framework for understanding how different listeners react when confronting adverse listening conditions. We focus primarily on peripheral psychophysiological measures, especially those related to the function of the autonomic nervous system, as these can provide insight into a listener's affective state continuously and in real time. Results of this research will provide a basis for developing therapeutic methods to address consequences of decisions involving emotional responses to adverse listening conditions, including self-isolation, hearing aid abandonment and rejection of hearing protection devices. Furthermore, we argue that such research will contribute to an understanding of the relationship between immediate, emotion-related physiological responses to communication-related stressors and long-term health issues faced by individuals with hearing loss and/or who are exposed to chronic high levels of noise. However, such research is also complicated by the fact that cognitive and affective responses affect the same physiological systems, and so care must be taken to carefully define the psychological and physiological constructs under investigation.

1.1. *The role of emotion in communication decisions*

Initial studies of spoken communication in adverse conditions focused on *performance*: How well can listeners recognize, understand, or respond to a speech signal? More recently, however, research has expanded to include emphasis on a broader range of underlying cognitive factors such as the *effort* required to successfully understand difficult speech, the *motivation* to do so, and the *fatigue* incurred by expending that effort (Pichora-Fuller et al., 2016 and associated articles). The importance of these concepts may be illustrated by the case of a listener in a noisy environment — perhaps someone attempting to hold a conversation during a crowded poster session at a professional society meeting. In this case, understanding a conversational partner may demand varying degrees of effort depending on the acoustic properties of the room, both physiological and psychological properties of the listener, and the linguistic and conceptual content of the speech being attended to (Lemke and Besser, 2016; Pichora-Fuller et al., 2016; Strauss and Francis, 2017). Additionally, the listener may have more or less motivation to expend that effort (note the distinction between demanded and exerted effort, see e.g. Strauss and Francis, 2017) depending on specific individual concerns (Matthen, 2016; Richter, 2016), and may become fatigued by the effort that is spent (Hornsby et al., 2016). Meanwhile, fatigue may in turn also affect the thresholds at which effort and motivation are felt to be sufficient to promote continued participation — a jet-lagged listener who feels tired might require greater motivation than one who feels wide-awake to maintain a necessary degree of effort without giving up on a conversation (Strauss and Francis, 2017; Matthen, 2016).

To this list we now add the emotions engendered by the communicative experience, with an emphasis on the feelings of *frustration* and *annoyance*. The study of emotional psychophysiology has, for various reasons both methodological and theoretical, tended to focus on stronger emotions such as anger and fear (cf. discussion by Barrett, 2017b). However, in considering emotional responses in adverse listening, it seems more likely that subtler, still negative emotions such as frustration and annoyance may be more relevant, and these have already been shown to be highly relevant for certain challenging contexts such as listening to speech in the presence of background noise.

In order to proceed, we must first provide a working definition of some key constructs, building on the consensus paper by Pichora-Fuller et al. (2016) and associated papers in the same volume although, due to the relatively recent integration of these concepts into the study of spoken communication there is still

Please cite this article in press as: Francis, A.L., Oliver, J., Psychophysiological measurement of affective responses during speech perception, Hearing Research (2018), https://doi.org/10.1016/j.heares.2018.07.007

considerable theoretical imprecision and heterogeneity of definition (cf. McGarrigle et al., 2014 on listening effort, for example) and further developments must be expected in the future (cf. Strand et al., 2018). Following Pichora-Fuller et al. (2016), mental *effort* may be defined as “The deliberate allocation of mental resources [such as attention and/or working memory] to overcome obstacles in goal pursuit when carrying out a task.” (p. 11S), which is also broadly consistent with the longstanding conception of effort proposed by e.g. Kahneman (1973). Note that we may also distinguish between the effort demanded by a task, and the effort actually exerted on that task (cf. Strauss and Francis, 2017). We will expand on this distinction in the section on Constructs, below.

Following Matthen (2016) we may consider *motivation* as the outcome of an evaluation comparing the effort that the listener is willing to devote to a particular task with the amount of effort the task demands. As Matthen writes, “when the cost that needs to be expended becomes greater than the benefit realized, your motivational arousal is reduced to zero” (29S-30S). Again, however, it may be useful to distinguish between initial motivation and moment-to-moment motivation. For example, participants may experience a level of motivation when first approaching a task that is associated with the over-arching goal of completing the task (Elliot, 2006; Gendolla and Richter, 2010). But this initial motivation may be distinct from the moment-to-moment degree of motivation to continue during the task (Matthen's *motivational arousal*). Following the discussion of Hornsby et al. (2016), there is also clearly an inverse relationship between motivational arousal or “motivation to continue on a task” (136S) and *fatigue:* a short-term, subjective state affected by ongoing assessment of performance and effort. For now we will treat motivational arousal and fatigue as two characterizations of the same phenomenon. Finally, *frustration* may be considered a negative emotion deriving from a feeling of being unable to, or especially prevented from, accomplishing a desired goal (García-León et al., 2003), while *annoyance* is simply a more general feeling of displeasure associated with some internal or external stimulus (for our purposes, often noise) (Belojević et al., 2003). We will expand on some of these definitions in the section on Constructs, below.

An impressionistic flowchart depicting some of the likely interactions between some of these concepts is shown in Fig. 1. This figure is meant to be conceptually similar to (but less comprehensive than) Fig. 1B presented by Pichora-Fuller et al. (2016), and is intended to link the important role of effort allocation (left of center, also central in the FUEL model) to affective physiological responses via the evaluative decision relating that effort expenditure to perceived performance and motivation (cf. Richter, 2016; also Strauss and Francis, 2017 and discussions of neuroeconomic approaches to listening effort by e.g. Eckert et al., 2016). We do not mean to suggest that this depiction is necessarily complete, nor do we intend at this time to argue that there is a fundamental distinction between our depiction here and that of the original FUEL model. Rather, this depiction is designed merely to highlight those parts of the putative system that relate most directly to *emotional* aspects of communicative decisions — the affective response to the analysis of relative cost and benefit of continuing in an effortful task, as well as the potential confound between the influence of affective/emotional vs. cognitive/motivational processes that is inherent in using physiological measurements to assess affect.

1.2. Emotions, affect and physiological response

Emotional states are generally considered to arise out of cognitive processing of unconscious visceral sensory information from the body (*interoception*). From this perspective, often codified as the *James-Lange theory of emotion*, emotions are physical (bodily) states made conscious (cf. Cacioppo et al., 1992; and especially Friedman, 2010, as well as related articles in that volume). However, the strictest version of the James-Lange theory has proved untenable in that it does not seem to be necessary to receive a full range of interoceptive feedback to feel emotion (Wiens, 2005). Furthermore, there is considerable debate in the field of affective psychology over whether, or to what degree, nameable emotions such as anger, annoyance, affection, or joy can be physiologically distinguished (Bradley, 2000). While some researchers have argued that a wide range of specific emotions can be identified through potentially unique patterns of physiological, especially autonomic, responses (Kreibig, 2010; Stephens et al., 2010), others (e.g. Barrett, 2017a; Siegel et al., 2018) have more recently begun to argue that emotions are conceptual categories, reflecting cognitive interpretations (categorizations) of internal states, and that these categories are learned from past experiences with similar combinations of external and internal states. For example, in the case of frustration, the emotional response can be thought of as a conscious awareness that something is impeding the ability to achieve a goal, or generally causing an adverse effect on

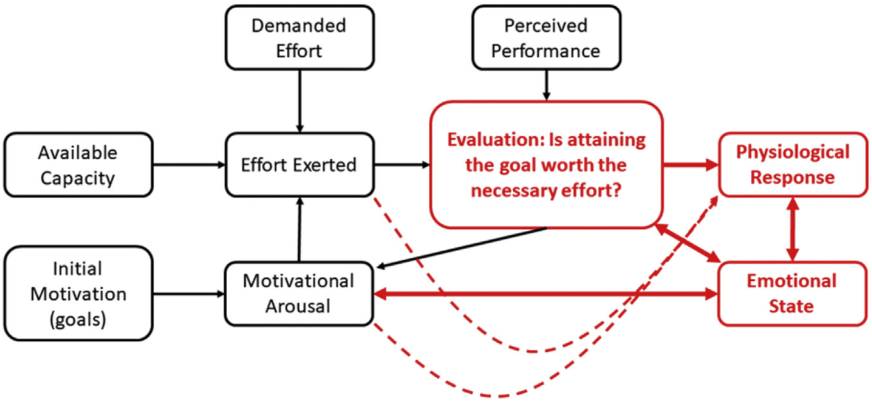

Fig. 1. Schematic diagram illustrating some hypothesized relationships between the emotional/affective constructs discussed in the present review (in red) and previously identified factors in communicative decision-making (in black) such as demanded and exerted effort and motivational arousal (Matthen, 2016; Pichora-Fuller et al., 2016; Richter, 2016; Strauss and Francis, 2017). See text for additional discussion. Dotted lines represent links between the psychological constructs of effort and motivation and physiological indicators such as the pupil dilation response to cognitive effort, and various cardiovascular and electrodermal indicators of motivation. The fact that both cognitive and affective constructs may influence the same physiological systems represents a central challenge to psychophysiological research on affective responses in communication.

Please cite this article in press as: Francis, A.L., Oliver, J., Psychophysiological measurement of affective responses during speech perception, Hearing Research (2018), https://doi.org/10.1016/j.heares.2018.07.007

performance (Rylander, 2004). Annoyance, in turn, may then be a general sense that something is interfering with one's overall state of wellbeing. Interoceptive information presumably contributes to both of these emotions, but cognitive states can also influence visceral states reciprocally (Critchley et al., 2013; Schulz and Vögele, 2015). Thus, rather than focusing on emotions as a sort of end-state, we choose to consider emotional responses to communicative challenges in terms of the behavior of an interactive system that integrates cognitive and affective/visceral responses to environmental stimuli in a mutually influencing manner.

In general, we can refer to the relationship between an organism and its environment as *affect* (i.e. “core affect” as discussed by Duncan and Barrett, 2007). Affect is a consequence of the continuous assessment of the compatibility between the current state of the environment (both internal and external) and the organism's current needs as well as needs anticipated due to awareness of longer-term goals. Following Bradley and Lang (2000) and Lang (2010), we can start by considering affect in the context of approach-avoidance theory as reflecting the engagement of physiological systems adapted for survival: Mobile organisms must be able to move toward desirable targets (food, mates) and away from undesirable ones (predators, noxious environments). When the environment disturbs homeostasis, body systems are activated to facilitate a response to that disturbance via descending pathways (preparing muscles to flee from the sound of a predator, preparing the gut to digest food in response to delicious smells, etc.). At the same time, ascending pathways from the body provide interoceptive awareness (the sense of the state of one's own body) of those physiological changes that in turn contribute to the emotional response (i.e. the sensations of changes in end-organ activity are interpreted in context as feeling afraid or feeling hungry). In a more general sense, active inference models of interoception suggest that the brain maintains an internal model of the world (including the internal milieu, i.e. physiological states) for regulating *all* aspects of allostasis (the process of maintaining bodily equilibrium), integrating a constant flow of information traveling along both descending and ascending pathways (Barrett, 2017a; Seth and Friston, 2016). Thus, measured changes in the activity of peripheral organs may serve as an index of changes in the current state of a continuously operating feedback loop integrating a predictive coding model, the current state of the organs of the body (interoception), and some evaluation of what must be done to bring those two states into concordance (allostasis) (Barrett and Simmons, 2015; Schulz and Vögele, 2015; Seth and Friston, 2016). In short, while the constructed nature of emotions means that it is not possible to characterize *emotional* responses uniquely according to measurements of signals generated by organs of the body, physiological measures, especially those governed by the autonomic nervous system, nevertheless provide information about the ongoing affective state of a listener and may be usefully interpreted as such. However, the relationship between physiology and psychology is complex, and the use of such measures must be approached carefully, as will be discussed in the next section.

1.3. *Considerations in relating psychology to physiology*

Richter and Slade (2017) present a concise and useful set of considerations when attempting to relate physiological measurements to psychological constructs. Here we build on two aspects of their discussion, one characterizing the possible relationships between psychological states and physiological measures, and one arguing for the importance of intermediate constructs. First, Richter and Slade (2017) explicate the taxonomy of psychophysiological relationships initiated by Cacciopo and colleagues (e.g. Cacioppo and Tassinary, 1990; see also Fairclough, 2009), and we adopt from this discussion the perspective that the intended goal of most research linking physiological measures to aspects of speech perception in adverse conditions seems to be to identify *markers* or perhaps *invariants*, of psychological states such as effort, attention, motivation, fatigue, distraction, and affect. Markers are defined as possibly context-dependent physiological measures that can be shown to be influenced by changes in a particular psychological state, and (crucially) *not* influenced by changes in other psychological states, while invariants are defined as context-independent markers.

We agree with Richter and Slade's (2017) argument that achieving such goals will be difficult because the autonomic nervous system by its very nature responds simultaneously and continuously to multiple psychological states as well as to the physiological states of end-organs themselves. Given the large number of potential combinations of psychological and physiological states, it would be impractical to attempt to demonstrate a strict absence of all other influences on a particular physiological measure. Therefore, most research investigating physiological responses to psychological manipulations will likely only be able to demonstrate the existence of *outcomes* (physiological responses that change as a result of changes in at least one psychological state in a context-specific manner) or perhaps *concomitants* (context-general outcomes), especially if focused on a single physiological measurement. Nevertheless there is still value in demonstrating *relatively* stricter relationships between affective states and physiological measures even if a demonstration of perfect correspondence is impossible. However, we suggest that even achieving a more gradient goal will require complex conceptualizations of both psychological states and physiological measures.

This suggestion in turn builds on a second important aspect of Richter and Slade's (2017) discussion, namely the idea from construct validation theory that the psychological states in which we are interested are themselves constructs in need of very specific definitions. To this we add that it may be useful to develop constructs on the physiological side as well. Specifically, we suggest that the physiological influence of complex psychological constructs may best be recognized through changes in *patterns* of physiological responses distributed across multiple, more basic physiological measures. If the goal of psychophysiological research in cognitive hearing science is to identify (nearly) one-to-one mappings between psychological states and physiological measures, we argue that incorporating a multivariate and theory-driven approach to characterizing both sides of the equation will improve the usefulness of the resulting research.

1.4. *Affective physiological systems*

In order to accurately characterize patterns of physiological response, it is important to understand the systems that govern those responses. Affective states have long been studied via measurements from bodily systems controlled by the autonomic nervous system (ANS). When a change in a physiological measurement appears to be correlated with the administration of a particular stimulus, it may seem reasonable to conclude that the physiological measurement is an indicator of the presence of that stimulus. However, the reality of physiological responses, perhaps especially with respect to the ANS, is far more complex. The ANS is the body's housekeeping system. Its most important function is to control bodily systems that are vital for keeping the organism alive: respiration, heartbeat, temperature regulation, digestion, and elimination (see Wehrwein et al., 2016, for a recent, comprehensive review). This function of the ANS can be defined as maintaining *homeostasis* (or, more properly, *homeodynamicity* or even *allodynamic regulation*), a condition of constantly shifting equilibrium

Please cite this article in press as: Francis, A.L., Oliver, J., Psychophysiological measurement of affective responses during speech perception, Hearing Research (2018), https://doi.org/10.1016/j.heares.2018.07.007

between physiological states of action and rest (Berntson et al., 2007). Thus, any measured changes in ANS state must be interpreted within this functional context. The ANS can be conceptualized in terms of three systems: the sympathetic, parasympathetic, and enteric nervous systems. The enteric nervous system is primarily responsible for digestion and elimination, and is typically discussed independently of both the rest of the ANS and the somatic nervous system. Although enterically-governed systems surely play a role in generating or signaling the affective responses that contribute to some sorts of decision making, such signals have not yet been investigated with respect to questions of speech perception and communication, thus we will not discuss the enteric nervous system further here.

The other two branches of the ANS, the sympathetic and parasympathetic, were traditionally seen as governing roughly complementary physiological domains, but that perspective has changed in recent years. The sympathetic nervous system (SNS) has also typically received more attention in literature addressing speech communication but parasympathetic nervous system (PSNS) functions are likely also quite relevant to the study of affective responses to challenges to communication. The SNS is traditionally associated with the need to respond physically to stimuli that appear to pose an immediate threat to the organism (the “fight or flight” response). Thus, SNS arousal is often thought of in terms associated with increasing preparedness for action. As SNS arousal increases, heart rate increases, blood supply is routed away from the periphery and toward large muscle groups, the pupils dilate, the palms and soles of the feet begin to sweat, and blood pressure increases. The parasympathetic nervous system has typically been considered mainly as a counterpoint to the sympathetic, serving to bring the body back from a state of heightened arousal toward homeostasis or a “rest and digest” state. As PSNS arousal increases, heart rate slows, blood supply is routed to the viscera and the skin, the pupils contract, and blood pressure decreases. However, PSNS activity can also serve a protective role in its own right (e.g. the pupillary light reflex contracts the pupil quickly in response to bright light), so it is inappropriate to assume that PSNS activity merely serves to “undo” sympathetically-driven arousal. Moreover, although the functional relationship between the SNS and PSNS was initially considered complementary, and early conceptualizations of arousal assumed they were necessarily reciprocal, more recent work suggests that the two systems can operate reciprocally, co-actively, and independently under different circumstances (Berntson et al., 1991; Cacioppo et al., 1994a,b; Cacioppo and Berntson, 1994; Norris et al., 2010). For example, low-level reflexive response patterns tend to be reciprocal, while those that also involve the influence of higher-level neural systems tend to be more flexible (Berntson and Cacioppo, 2007). Thus, when attempting to interpret patterns of ANS response in speech communication contexts (i.e. contexts that involve the engagement of mulitiple, high-level cognitive systems), it is advisable to measure both sympathetic and parasympathetic responses, and not to assume that increased activity in one system necessarily implies decreased activity in another.

Similarly, while earlier research typically assumed that responses of a given system (SNS or PSNS) were unitary, in the sense that, for example, all end-organs innervated by the SNS were expected to exhibit comparable patterns of activation in response to a given stimulus, this is no longer assumed to be the case (see review by Goldstein, 2013). Psychophysiological studies have identified a pattern known as *directional fractionation* (Lacey, 1967; see discussion by Bradley and Lang, 2000) or *response fractionation* (Barry, 2009), whereby some end-organ responses appear to reflect SNS arousal while others, also innervated by the SNS, show less arousal or even some degree of withdrawal under the same conditions. Anatomical studies have also identified distinct types of neurotransmitter receptors on different end organs, including (at least) alpha- and beta-adrenergic receptors (associated mainly with the peripheral vascular system and the heart muscle tissue, respectively) as well as some end organs (sweat glands and piloerectory muscles in the skin) that are stimulated cholinergically instead of adrenergically. Thus, it should not be surprising that different end organs may exhibit distinctive patterns of response that may ultimately be related to the role each organ plays in allodynamic regulation (Bradley, 2009; Lang, 2010; Stemmler, 2004).

It is also overly simplistic to associate the sympathetic nervous system solely with the activation of aversive/defensive responses, or the parasympathetic with appetitive/approach responses (see discussion by Lang and Bradley, 2010). Sympathetic activation occurs, for example, during sexual arousal, which involves an appetitive/approach-type response. Similarly, as a first approximation, the concept of arousal or intensity of response appears to map easily onto simple increase in end-organ activity. However, because most end-organs are innervated by both the SNS and PSNS, a change in a particular organ's response could be due to changes in the influence of either, or both systems. For example, an increase in heart rate could result from increased (adrenergic) sympathetic nervous system response, or (as is more typically the case) from withdrawal of the parasympathetic (cholinergic) down-regulation of the natural rate of contraction of the sinoatrial node, while increased pupil dilation may result from either (or both) withdrawal of parasympathetic arousal and increased sympathetic arousal.

There are ways to distinguish between SNS and PSNS influences on a given organ. For example, because the SNS functions both via direct nervous control and also by the release of catecholamines (epinephrine, norepinephrine) from the adrenal glands into the bloodstream, it has both a rapid as well as a longer-term time-course of operation. While synaptically-released norepinephrine is reabsorbed within a few milliseconds by the transmitting neuron, there is no corresponding mechanism to extract blood-borne norepinephrine. Thus, the influence of adrenal medullary activity may persist in the body for much longer than that of synaptic norepinephrine, resulting in prolonged heighted arousal of adrenergic systems throughout the body, even as direct synaptic influences on a specific organ have ceased. In contrast, the PSNS operates primarily via direct innervation, and the breakdown of its primary neurotransmitter, acetylcholine, in the synaptic cleft is extremely rapid (McCorry, 2007). Therefore, changes in PSNS arousal tend to have much more immediate and less persistent effects than do those of the SNS, and this distinction may help in disentangling the contributions of the two systems to a single end-organ response. Such considerations may be particularly useful in cases in which activity in different branches of the SNS may help to distinguish between the influence of different psychological constructs on a single measurement from a given end organ (see, for example discussion of the distinction between cognitive and affective influences on the pupil dilation response below).

In summary, when attempting to characterize autonomic responses to complex tasks and/or under complex stimulation, such as when listening to speech in noise, it is advisable to incorporate assessment of both SNS and PSNS activation, because (as we shall see) their respective activity may often be broadly associated with different sorts of psychological constructs. However, it is important not to assume that the two systems interact either reciprocally or linearly over time (Buijs, 2013; Goldstein, 2013). Combinations of measurements made from multiple, anatomically unrelated end-organs are more likely to give a more complete picture of how the body is responding to the context and conditions of the task than those from a single organ or system.

2. Constructs

Our long-term goal is to develop methods for using physiological measurements to quantify how an individual listener is *feeling* during a particular challenge to listening. This means that, in addition to looking for patterns of response across multiple physiological measures, we must also seek to distinguish affective responses from those arising from other psychological constructs such as cognitive effort and motivation. Our goal here is to characterize psychological constructs in terms that are easily related to (patterns of) physiological measures, and yet that may ultimately be distinguished from one another in terms of their effects on measurable responses (both behavioral and physiological) in a given context or set of contexts.

2.1. Arousal and valence

Affective physiological responses are often characterized in terms of *arousal* and *valence*, intermediate constructs that mediate between emotions and direct physiological measurements (Bradley and Lang, 2000; Bradley and Lang, 1994). The terms *arousal* and *valence* can be understood most easily within the context of approach-avoidance theory. Mobile organisms must be able to move toward desirable targets (food, mates) and away from undesirable ones (predators, noxious environments). Thus, affect may be characterized in terms of two primary, orthogonal dimensions: *hedonic valence* (pleasure-displeasure) and *arousal* (calm-excited) (Bradley and Lang, 2000; Bradley and Lang, 1994). In approach-avoidance theory, the dimension of valence (pleasure-displeasure) maps easily onto the concept of approach-avoidance, such that approaching desirable targets should be associated with positive affective responses (and thus pleasurable feelings) while being unable to avoid potentially harmful ones should be unpleasant.

Arousal, on the other hand, maps well onto the concept of preparation for action. As the environmental pressure to act increases, so too should the organism's readiness to do so (though the appropriate action to be taken will depend on specifics of the context and the individual). In using physiological measurements to investigate individuals' affective state, we must therefore consider signals that indicate the degree to which the organism is preparing for action (arousal) and/or whether that action is more approach- or avoidance-oriented (valence). The most common measurements that can be obtained easily from different end-organs differ in the degree to which they reflect arousal and valence, and also differ in the degree to which they are influenced by other aspects of the internal and external environment (i.e. cognitive processes, metabolic demands).

Arousal and valence are often treated as independent dimensions structuring an affective “space.” While both subcortical (Styliadis et al., 2015) and cortical (Dolcos et al., 2004) evidence suggests a degree of independence between these two dimensions, autonomic measures show a complex interaction between valence and arousal that also varies across sex and age (Gomez et al., 2016). Moreover, different environmental stimuli (stressors) may induce different degrees of responsiveness on different affective systems (Skoluda et al., 2015), meaning that a complete characterization of a physiological response may require some information about the nature of the causal task and environment (i.e. the measurements we use are likely context-dependent, at least to some degree, cf. discussion by Richter and Slade, 2017).

2.2. Effort and motivation

There has been considerable work on defining cognitive constructs such as listening effort within the field of cognitive hearing science, so we will focus here only on those aspects that seem most relevant for distinguishing between cognitive and affective responses. First, it is important to distinguish between demanded effort (i.e. the effort required to accomplish a particular task) and the effort that is actually exerted by a particular person attempting to accomplish the task (Strauss and Francis, 2017). From a physiological perspective, the relationship between task demand and expended effort need not be direct and must include at least some reflection of the importance of succeeding at the task, which we call initial motivation in Fig. 1 (cf. Richter, 2016). Here, our concern is primarily with physiological correlates of exerted effort, and how or whether they may be distinguished them from affective responses.

Although exerted effort is typically described in terms of consumption of resources, attempts to identify a relationship between the expenditure of cognitive effort and physiological consumption of available metabolic resources (i.e. blood glucose) have shown inconclusive results (Kurzban, 2010), and suggest the need for incorporating other constructs such as motivation (Molden et al., 2012). For our purposes, it is sufficient to consider the limited resources that are spent through the exertion of cognitive effort as constructs in their own right, particularly attention (Strauss and Francis, 2017) and/or working memory (Pichora-Fuller et al., 2016; Wingfield, 2016). Thus, in measuring physiological affect, it is important to design studies in such a way that the exertion of cognitive effort in the form of applying selective attention and/or working memory capacity can be assessed independently from measures that are likely to (also) reflect affective constructs such as arousal or valence.

2.3. Distraction and annoyance

In the study of human responses to environmental and workplace noise, a distinction is often made between *distraction* and *annoyance* (Kjellberg et al., 1996) and the interaction between these two constructs presents a useful context in which to concretely explore some of the theoretical considerations we have just outlined. In this case, distraction may be defined as the capturing of attention by sound events unrelated to the listener's task or goal. In an office context, these are frequently voices, telephones or footsteps (Pierrette et al., 2015). From our perspective, we consider distraction to be a cognitive construct because it is related to the conceptualization of cognitive effort in terms of demand on limited (attentional) processing capacity (cf. discussion of resource models by Pichora-Fuller et al., 2016; Strauss and Francis, 2017). Specifically, distraction is the capture of attention by task-irrelevant sounds, and by taking up limited attentional resources it can reduce the cognitive capacity available for processing task-relevant information (Fairnie et al., 2016; Francis, 2010; McCoy et al., 2005; Strauss and Francis, 2017; Surprenant, 2007; Tun et al., 2009), thereby diminishing performance.

Annoyance, on the other hand, is much more clearly emotional in nature. Annoyance due to the presence of external noise, for example, is typically quantified in terms of responses to surveys (e.g. Kryter, 1959; Shepherd et al., 2010) but there is increasing interest in identifying physiological correlates of annoyance (Shepherd et al., 2016). Subjective measures of distraction and annoyance are correlated, and both are related to individual differences in self-assessed sensitivity to noise (Kjellberg et al., 1996). Kjellberg et al. (1996) argue that it is important to consider distraction independently from annoyance because distinct environmental variables contribute significantly to each of them, although they conclude that they are not strictly orthogonal; distraction likely serves as a contributing (but not the sole contributing) factor in noise annoyance. By considering the concept of distraction in terms of a resource-based conceptualization of

Please cite this article in press as: Francis, A.L., Oliver, J., Psychophysiological measurement of affective responses during speech perception, Hearing Research (2018), https://doi.org/10.1016/j.heares.2018.07.007

effort (e.g. Pichora-Fuller et al., 2016), there are two ways in which distraction might give rise to similar physiological responses: Directly, by loading attentional processes that provoke physiological responses related to cognitive demand (i.e. parasympathetic withdrawal-related pupil dilation, see below), and indirectly when the realization that one is unable to complete a particular task to the desired degree of performance causes an affective response that is perceived as the emotion of annoyance (see also discussion by Kjellberg et al., 1996). In the first case, one might expect remediation that alleviates cognitive demand to be more effective, while in the second remediation addressing the emotional/affective response may be more effective. Research on reducing distraction from noise, e.g. in the workplace, would therefore benefit from the identification of physiological response patterns that are uniquely indicative of cognitive as compared to affective responses, or vice versa.

3. Measurements

In this section, we discuss some of the most common psychophysiological measurements employed in research on speech perception, specifically focusing on whether or how it might be possible to distinguish between responses reflecting affective psychological constructs (i.e. arousal and/or valence) vs. cognitive ones (especially effort, attention, and working memory).

3.1. Pupil dilation

The single psychophysiological measure most closely identified with cognitive hearing science is the pupil dilation response. The muscles controlling the diameter of pupil aperture are innervated both sympathetically and parasympathetically. Sympathetic innervation governs pupil dilation and tends to be somewhat slower to respond, while parasympathetic innervation controls pupil contraction and responds more quickly. In terms of magnitude, the most significant effects on pupil diameter result from the light reflex, a parasympathetically-controlled response: The pupil constricts rapidly in bright light and dilates in dim, with a latency as small as 200 ms. This light reflex can result in changes of multiple millimeters of diameter, but smaller changes can also reflect a variety of affective and cognitive responses to stimulation (see Ch. 12, Andreassi, 2007). Both cognitive and affective states can affect pupil dilation, highlighting the need to distinguish between the physiological consequences of different psychological constructs.

3.1.1. The cognitive pupillary response

The pupil dilation response has long been associated with tasks requiring the application of cognitive effort (Beatty, 1982; Kahneman, 1973) including listening effort (Zekveld et al., 2014). In terms of specific cognitive mechanisms, pupil dilation has been associated with the engagement of selective attention (Wierda et al., 2012) and working memory (Goldinger and Papesh, 2012; Koelewijn et al., 2012) as well as with intermediate constructs such as general arousal related to task demand (Kahneman, 1973), and engagement in the task (Gilzenrat et al., 2010; Kahneman et al., 1968). Steinhauer et al. (2004) used pharmacological methods to determine that the increased pupil dilation associated with increased cognitive demand during a serial addition task resulted from relaxation of parasympathetically governed pupillary constriction, resulting in observable demand-related pupil dilation. It therefore seems likely that the pupil dilation responses associated with increases in other cognitive demands, including those associated with communication, also result from relaxation of parasympathetic control.

3.1.2. The affective pupillary response

In addition to cognitive effort, pupil dilation also plays a significant role in signaling affect (Hess, 1975) and studies by Bradley and colleagues (Bradley et al., 2008, 2017) demonstrated the existence of a pupil dilation response associated with viewing images with strong emotional content (erotica, violence/mutilation) (see also Partala et al. (2000) for similar results in response to emotionally evocative sounds). Bradley et al. (2008, 2017) found that this emotionally associated dilation response co-varied in magnitude with another physiological measure (EDA, see below) that is governed by purely sympathetic innervation. However, the emotional pupil dilation response did *not* co-vary (inversely or otherwise) with parasympathetic arousal/withdrawal as indexed by a different physiological measure (heart rate deceleration, see below). These findings suggest that the affective pupillary response is governed mainly by SNS arousal. Recent research by Wetzel et al. (2016; Widmann et al., 2017) showed that principal components analysis may be effectively employed to decompose the pupillary response into separate PSNS— and SNS-related components, and confirmed that emotional arousal has a fundamentally sympathetically mediated effect on pupil dilation.

3.1.3. The pupillary response in cognitive hearing science

In the cognitive hearing science literature, pupil dilation has typically been associated not with the specific, proximal activity of either the sympathetic or parasympathetic branches of the autonomic nervous system, but rather with activity in the more centrally located locus coeruleus-noradrenergic (LC-NA) system (Kuchinsky et al., 2013; 2014; 2016a; 2016b). Experimentally, LC activity is strongly associated with pupil dilation due to increasing visual attentional load (Murphy et al., 2014), and pupil dilation is argued to reflect increased listening effort from a variety of causes (Kramer et al., 1997; Kuchinsky et al., 2013; Koelewijn et al., 2014; Winn et al., 2015; Winn, 2016; Zekveld et al., 2011). The LC plays a significant role in the regulation of attention and arousal (Berridge and Waterhouse, 2003) and innervates a variety of nuclei in the hypothalamus that in turn govern autonomic responses. With respect to these loci, because the LC-NA is noradrenergic, it is excitatory with respect to sympathetic processes and inhibitory when affecting parasympathetic ones (Samuels and Szabadi, 2008). Thus, it may serve to increase pupil dilation either (or both) via a sympathetic or parasympathetic pathway. These pathways, in turn, may or may not be influenced by other cognitive (likely parasympathetic) or affective (likely sympathetic) processes. Based on the pharamacological studies described above, it seems plausible that the primary effect of the LC-NA on pupil dilation during cognitively demanding listening is mainly parasympathetically mediated (i.e. cognitive). However, if the context that induces listening effort is emotionally fraught, or if the sensation of effortful listening evokes an emotional response in a particular listener (i.e. frustration), it is also possible that pupil dilation may arise via a sympathetic route as well. Statistical signal processing methods such as those described by Wetzel and colleagues may serve to distinguish these influences in future research, allowing a more nuanced understanding of the bases for patterns of physiological response to listening to speech in challenging conditions.

Determining the degree to which a pupillary response to challenging listening conditions is sympathetically vs. parasympathetically governed is important for practical as well as theoretical reasons. For example, compared to younger adults, older adults typically show reduced absolute pupil diameter (measured at rest, in lighted conditions) and also a comparative reduction in light response. However, pupil dilation measured in the dark (when parasympathetic control is minimized) is similar across age groups. This pattern suggests that there is an age-related

Please cite this article in press as: Francis, A.L., Oliver, J., Psychophysiological measurement of affective responses during speech perception, Hearing Research (2018), https://doi.org/10.1016/j.heares.2018.07.007

shift in the balance between sympathetic and parasympathetic influence on pupil diameter, most likely involving greater age-related decline in sympathetic as compared to parasympathetic function (Bitsios et al., 1996; Pozzessere et al., 1996). Thus, while the pupil dilation response is clearly a useful tool for investigating changes in demand on cognitive processing in the context of speech communication, accurate interpretation of comparisons across ages and across contexts ultimately depends on whether the effects under investigation derive from either or both cognitive or affective sources, and this determination may be facilitated by methods that better distinguish between sympathetically and parasympathetically mediated components of the pupil dilation response. Such methods may include both sophisticated statistical analyses such as those described by Wetzel and colleagues, and also comparison across multiple end organs innervated by the same underlying system (Bradley et al., 2017) (though this latter method may be complicated by directional fractionation).

3.2. Electrodermal responses

There do exist cases in which there is no potential for conflating sympathetic and parasympathetic influence on a physiological response, but here, too, care must be taken to understand the interacting influence of multiple physical and psychological states. For example, electrodermal activity (EDA) refers to changes in properties of the skin that affect electrical conductance through the skin as a result of eccrine sweat gland activity (Andreassi, 2007; Boucsein, 1992; Dawson et al., 2007). Eccrine sweat glands are innervated purely sympathetically but, unlike most other sympathetic end-organs (and like may parsympathetic end-organs) they are cholinergic, not adrenergic. Thus, they are not strongly affected by circulating catecholamines released from the adrenal glands under broad sympathetic arousal and may primarily reflect more immediate influences on the SNS. These glands play a significant role in temperature regulation, but also respond to psychological and emotional stimuli ("arousal sweating"), though this depends somewhat on their location (Dawson et al., 2007). It has been argued that arousal sweating facilitates preparation for high levels of motor activity (fight or flight) by cooling the surface of the body (Edelberg, 1973), by improving grip (Darrow, 1933), or by increasing skin resistance to physical injury (Wilcott, 1967).

Measures of skin conductance can be characterized according to the span of time over which they unfold as either *tonic* (unfolding slowly) or *phasic* (unfolding quickly, often in response to a single stimulus) (cf. discussion by Dawson et al., 2007). The most common tonic measure is *skin conductance level (SCL)*, which is measured as the level of conductance. Phasic measures are generally based on *skin conductance responses (SCRs)*, which are transient increases of conductance over a relatively short period of time. SCRs are often evoked by the onset of a stimulus but also arise spontaneously (i.e. in the absence of an identifiable stimulating event). The (mean) magnitude and/or latency of SCRs can be quantified as phasic measures of EDA, while the number of spontaneous SCRs (also called non-specific SCRs) in a given span of time may be used as a measure of tonic EDA along with or instead of SCL. Although EDA is relatively easy to record and quantify, reliability of response may vary considerably across individuals, possibly as a function of information processing abilities, schizophrenia, and psychopathy (Dawson et al., 2007) but also as a function of age (Lau et al., 2001).

Results of some studies of adverse listening conditions (Francis et al., 2016; Mackersie and Calderon-Moultrie, 2016; Mackersie and Cones, 2011; Seeman and Sims, 2015) suggest that EDA may be useful for examining factors related to selective attention in speech perception, though Cvijanović et al. (2017) and Mackersie et al. (2015) also reported null results for EDA-based measures. Across these studies, the overall pattern of results suggests that electrodermal responses are sensitive to the attentional demands of a task because significant effects on EDA were found with (a) increased competition in a dichotic digits task, (b) increased speaking rate, and (c) informational but not (d) energetic masking. Nevertheless, given the extreme heterogeneity of methods of stimulation and measurement across these studies, further research is necessary to identify consistent patterns of EDA response in challenging speech perception contexts.

In the affective literature, EDA is prominently associated with the dimension of *arousal,* in that increased SCL, SCR amplitude, and rate of spontaneous SCRs are all associated with a wide range of emotions with both positive (anticipatory pleasure from visual images, amusement) and negative (fear, anxiety, disgust, anger) valences (Kreibig, 2010). Cognitively speaking, SCL has been associated with a variety of cognitive constructs that may or may not be related. Observed correspondences include increased SCL associated with increased demand on working memory, e.g. in an N-Back task (Mehler et al., 2012), and decreases in SCL associated with decreases in sustained attention (vigilance) (Davies and Krkovic, 1965). In general, SCR amplitude is also sensitive to stimulus intensity, and declines with repeated exposure (habituation) (Dawson et al., 2007). Thus, EDA, and particularly SCRs, may serve as a marker of the engagement of working memory and/or selective attention, especially with respect to emotionally salient stimuli (Andreassi, 2007; Bradley, 2009; Cohen, 2014) Note that the distinction or relationship between working memory and selective attention must clearly be addressed in order to effectively relate physiological responses to either (or both) constructs, but this is a topic far beyond the scope of the present paper (cf. Cowan, 2017; Lavie, 2010). More specifically, SCRs play an important role in the characterization of the *orienting response (OR)*, a multi-organ response associated with the exogenous capture of attention (Bradley, 2009) (see below).

In short, despite exhibiting a high degree of individual variability, EDA has the potential to serve as a useful marker of the psychological construct of arousal. However, arousal may be influenced by both cognitive and emotional stimulation so EDA measures are best used in conjunction with other measures as discussed below.

3.3. Cardiovascular responses

A large number of measurable cardiovascular behaviors have been linked to both emotional and cognitive demands. Cardiac responses are implicated in one way or another in virtually every emotional response that has been studied in detail (see Kreibig, 2010 for examples), while heart rate and heart rate variability (HRV) in particular, have been associated with a variety of cognitive processes (Berntson et al., 2017). For the sake of brevity, here we will only discuss those that have been most frequently addressed in the existing literature on speech communication in adverse conditions.

Only a few cardiovascular measures have been employed thus far in the study of speech perception in adverse conditions. These include cardiac measurement of (changes in) heart rate (HR) and heart rate variability (HRV), and vascular measurement of blood volume (BV) and blood volume pulse amplitude (PA). Because the heart is innervated by both sympathetic and parasympathetic pathways, measurements related to heart behavior itself can reflect the influence of either or both of these systems. In contrast, because vasoconstriction is governed almost exclusively by the SNS, measures related to this response can be used to isolate sympathetic activity. We will therefore address these two types of measures separately.

Please cite this article in press as: Francis, A.L., Oliver, J., Psychophysiological measurement of affective responses during speech perception, Hearing Research (2018), https://doi.org/10.1016/j.heares.2018.07.007

3.3.1. Cardiac responses

As with EDA data, heart rate values are often normalized against a resting baseline value, and thus may be expressed as a change in beats per minute (BPM) or relative BPM. It is probably more accurate to use heart period (sometimes called R-R interval) or change in R-R interval when participants are likely to have significantly different baseline heart rates, as for example when comparing participants of very different ages (Berntson et al., 1995). Changes in heart rate are typically modulated by both sympathetic and parasympathetic activity. Sympathetic influence tends to be somewhat slower to affect the heart than parasympathetic control, and also has a narrower range of effect in terms of change to heart rate, but has a greater influence on the strength of heart muscle contraction. In contrast, the parasympathetic system reacts more quickly (changes in parasympathetic arousal may be observed within the span of a single heartbeat) and affects heart rate to a much greater degree than does sympathetic influence. Further complicating interpretation of heart rate in terms of the influence of these two systems is the fact that both arousal and withdrawal of sympathetic and parasympathetic stimulation can affect heart rate. Thus, heart rate may slow due either (or both) to an increase in parasympathetic arousal or a decrease in sympathetic arousal, while heart rate might rise due to either (or both) a decrease in parasympathetic or increase in sympathetic arousal (Berntson et al., 2007).

Studies of HR in adverse listening conditions have shown mixed results, likely because of the wide variety of stimuli and methods used thus far. For example, Francis et al. (2016) asked listeners to repeat simple sentences and observed a small decrease in HR a few seconds after the onset of speech. This decrease was present for easy to understand speech (unmasked and undistorted), but was stronger when the speech was more difficult to understand because it was produced by a low-quality computer speech synthesizer, or masked with noise, or with two-talker babble. Seeman and Sims (2015) also found a significant difference in HR in a dichotic digit task with increasing task complexity, but in this case they computed average heart rate over a 2-min span containing multiple trials in each condition. In contrast, Mackersie and Cones (2011) and Cvijanović et al. (2017) found no significant effect on HR of increasing task difficulty in a dichotic digits task, and a cafeteria noise-masked cooperative communication task, respectively. This is particularly interesting because the dichotic digits task used by Seeman and Sims (2015) was explicitly modeled on that used by Mackersie and Cones (2011) and both used HR values averaged over blocks of time containing multiple trials. However, while Seeman and Sims (2015) calculated HR from ECG, Mackersie and Cones (2011) calculated it from fingertip pulse plethysmograph, as did Francis et al. (2016). Given these differences in methods, and particularly the lack of control or consideration of other affective or metabolic factors that might affect HR in all of these studies, it is difficult to identify a definitive effect of listening effort on heart rate at this point. Further research is clearly necessary to determine whether, or under what conditions, HR may be affected by listening task demands.

In order to distinguish between parasympathetically and sympathetically governed changes in cardiac behavior, researchers have typically sought to identify measures that reflect activity of only one of the two systems by chemically blocking the neurotransmitter systems involved in either sympathetic or parasympathetic innervation of the heart (Shaffer et al., 2014). Based on such studies, pre-ejection period (PEP) and respiratory sinus arrhythmia (RSA) have emerged as reasonably simple measures associated with SNS and PSNS cardiac influence, respectively (Berntson et al., 1994; Berntson et al., 1994; Cacioppo et al., 1994b). PEP is a measure of the time of ventricular contraction and the opening of the valve releasing blood from the ventricles into the atria (Newlin and Levenson, 1979). PEP thus reflects strength of ventricular contraction, which is strongly associated with sympathetic cardiac innervation. Measurement of PEP can be acquired using impedance cardiography but has not yet been employed in the study of speech in adverse conditions, though it has potential (see Richter, 2016). In contrast, the square root of the mean squared difference between successive heart periods (RMSSD) is often used as a measure of parasympathetic influence on the heart. Because the RMSSD depends on comparison of successive periods of the ECG waveform, it is sensitive to rapid changes in HR, and these are likely largely due to vagal (parasympathetic) influences because of the greater speed of reaction of the PSNS as compared to the SNS (Berntson et al., 1993). More recently, however, Berntson, et al. (2005) showed that RMSSD is less reliable for estimating within-subject PNS activity especially across conditions in which base heart rate may vary. Thus, while this measure may be useful for establishing trait-like HRV characteristics (i.e. between-subject comparisions within a single condition) it is not ideal for the kinds of within-subject designs more commonly used in hearing science research.

It may also be possible to separate sympathetic from parasympathetic innervation by examining different measurements of heart rate variability (HRV) based on various mathematical analyses of the ECG signal (Berntson et al., 2017). Researchers have identified specific frequency bands in the spectral decomposition of the ECG signal that are particularly useful for ANS-related interpretation (Shaffer et al., 2014). The so-called high frequency band (often abbreviated HF-HRV) lies between about 0.12 (or 0.15) and 0.4 Hz, is often treated as a proxy for respiratory sinus arrhythmia (RSA). Like RMSSD, RSA is a temporal measure typically considered to be an index of parasympathetic activity. Under normal circumstances, the heart period is slightly shorter during inspiration and slightly longer during exhalation, and RSA is a measure traditionally derived by comparing the heart period during inspiration and expiration (Grossman et al., 1990). Given that frequency-based analyses such as HF-HRV alone may not be sufficient for quantifying PSNS activity, simultaneous evaluation of respiration and heart period is important for accurately quantifying RSA (Quintana et al., 2016).

Although there is a broad consensus that changes in RSA within a given individual likely reflect changes in parasympathetic arousal, there can also be significant differences across individuals, notably as a function of age (De Meersman, 1993). It has also been argued that differences in resting or baseline RSA may be associated with differences in a variety of relevant traits including cognitive flexibility (Thayer et al., 2009) and emotional state and traits (Oveis et al., 2009). Other, lower frequency bands have been identified (e.g. LF-HRV in the 0.04–0.15 Hz range) and linked to sympathetic arousal or a combination of parasympathetic and sympathetic arousal, and their association with a variety of psychophysiological properties has been investigated. For example, the ratio of LF-HRV to HF-HRV is sometimes used as an indicator of autonomic balance. However, the physiological basis of such conclusions is less clear, and there is less consensus as to their significance (Goldstein et al., 2011). In particular, Heathers (2014) argues persuasively that current methods for quantifying HRV-related metrics without reference to respiration are not well-justified, and further work is necessary to establish more physiologically grounded norms.

Results from studies investigating HRV while listening to speech in adverse conditions are mixed. Dorman et al. (2012) found that HRV decreased as SNR decreased in normally hearing listeners performing a sentence recognition task masked by varying levels of an unspecified type of noise. Similarly, Seeman and Sims (2015) found progressively greater changes in HRV compared to baseline as SNR decreased, and also when a digit recognition task changed

Please cite this article in press as: Francis, A.L., Oliver, J., Psychophysiological measurement of affective responses during speech perception, Hearing Research (2018), https://doi.org/10.1016/j.heares.2018.07.007

from diotic to dichotic (increasing demand on selective attention), while Mackersie et al. (2015) found a change in HRV with decreasing SNR only in listeners with hearing impairment and not in normally hearing listeners. And, finally, Cvijanović, et al. (2017) found no significant change with decreasing SNR in HRV frequency bands related to both SNS and PSNS and SNS arousal (LF-HRV and the ratio of LF to HF-HRV, respectively). This somewhat mixed pattern of results certainly suggests the need for more research on the relationship between HRV (especially HF-HRV or RSA as an indicator of parasympathetic down-regulation) and perception of speech in adverse conditions. For this endeavor to be successful, an additional complicating factor must be addressed, namely the observation that resting HRV may itself serve as a predictor of some aspects of cognitive performance, especially when the stimuli used in cognitive testing have strong emotional significance.

As discussed by Thayer et al. (2009), there is a considerable body of research suggesting that individuals with higher resting HF-HRV show better performance on cognitively demanding tasks involving sustained attention, executive function, working memory, and response inhibition as compared to those with lower HF-HRV. These findings support a hypothesis of *neurovisceral integration* in which central (frontal, cortical) systems associated with executive function modulate (especially inhibit) subcortical systems to permit the organism to respond rapidly to changing environmental demands, perhaps especially when such demands have a significant affective valence (i.e. selective attention between faces with threatening vs. non-threating expressions). According to this hypothesis, vagally-mediated autonomic signals such as HF-HRV can directly reflect the responsivity of cortical systems involved in executive function. However, recent neuroimaging research employing a large sample of participants (Jennings et al., 2015) suggests that such a broad interpretation of the link between HF-HRV and executive function may not be warranted, and, indeed, some of the apparent correlations may not obtain in all cases. Further research is necessary to understand the relationship between HF-HRV and executive function before strong predictions may be made regarding its role in understanding speech in adverse conditions.

3.3.2. *Vascular responses*

Measurements obtained from the peripheral cardiovascular system include blood pressure, blood volume, and blood volume pulse amplitude (BVPA). Blood pressure measurements have not yet been studied in the context of speech perception in adverse conditions, but we mention them here because of their potential importance in the context of the relationship between long-term cardiovascular health and exposure to noise and hearing impairment (see below) and because of the important role that baroreceptor feedback plays in the autonomic loops that govern cardiac responses (Klabunde, 2011) and possibly cognitive performance (Duschek et al., 2009). Measures of blood volume and BVPA have been shown to *decrease* (reflecting increased blood vessel wall resistance due to increased sympathetic nervous system arousal) in response to increasing demands of cognitive tasks such as the Stroop task (Tulen et al., 1989) and mental arithmetic (Goldstein and Edelberg, 1997). Such decreases have been linked specifically to the increased investment of mental effort in a task, such that, for example, pulse amplitude decreases parametrically with increase in working memory load (Iani et al., 2004). Most studies of cognitive effects on BVPA have used averaged measurements over at least a minute, but, as with all cardiovascular measures, more subtle differences may be identifiable with suitable attention to the time-course of changes (Lackner et al., 2014) (see also discussion by Potter and Bolls, 2012, on the importance of time in psychophysiological measurement). Decrease in BVPA is also associated with mostly negative emotions (fear, disgust, anger, sadness, and anxiety) (Kreibig, 2010) and thus may be associated with annoyance or frustration as well (cf. suggestion by Francis et al., 2016). However, this has not, to our knowledge, been investigated yet. Given the relative rapidity within which pulse amplitude can change, future research evaluating BVPA responses to communicative tasks should examine patterns of response at both the second-by-second level as well as block level averages.

Measurement of blood volume pulse amplitude (BVPA) is not yet common in the study of speech perception, but results from our lab seem promising. For example, Francis et al. (2016) found that listeners showed a drop in BVPA a few seconds after stimulus onset, and this drop was significantly greater in conditions in which the stimulus was masked either by steady-state speech-shaped noise or by two-talker babble. It is possible that this response pattern indicates an effect of greater cognitive demand in the masked conditions as compared to the unmasked, undistorted condition and also with respect to the unmasked but computer synthesized condition. However, another possibility is that the drop in BVPA may be related to an affective response to the presence of noise (or any interfering signal) itself (i.e. frustration or noise annoyance) (Francis et al., 2016). This illustrates some of the difficulties faced when attempting to distinguish between the effects of different psychological constructs on a single physiological response.

3.3.3. *Cardiovascular measures in the study of noise annoyance*

Psychophysiological, especially cardiovascular, measures have been employed with some success in the study of noise annoyance, and there is a long and growing interest in this area because of the observed relationship between environmental and occupational noise exposure and cardiovascular health (Babisch, 2011; Davies et al., 2005; Davies and Van Kamp, 2012; Passchier-Vermeer and Passchier, 2000; Parsons, 2007; Stansfeld and Matheson, 2003; WHO, 2011). Much of this work focuses on measures associated with blood pressure because of its association with cardiovascular disease, rather than the measures typically used in studies of effects of noise on communication specifically. Nevertheless, the physiological relationship between blood pressure and sympathetic control of vascular tension indexed by pulse amplitude suggests a plausible connection between the two and there are a few examples of studies relating them specifically.

For example, in one of the earlier studies in this domain, Kryter and Poza (1980) found a noise-related increase in vasoconstriction (decrease in BVPA) during exposure to noise. Interrupted noise appeared to have a weaker effect than steady-state noise but given the relatively rapid and short-term nature of BVPA responses to noise this may have been due to the averaging employed in their study (as they point out). They also observed that effects were stronger for wide-band than high-frequency narrow-band noise and did not correspond clearly to other measures of ANS responsivity (heart rate, in particular). Ultimately, they conclude that vasoconstriction may reflect an “aural reflex” type of response rather than stress per se.

However, subsequent research lends stronger support to the idea that acute noise exposure does affect a broader range of autonomic, especially cardiovascular, responses (see Lusk et al., 2002 for a review and additional supporting data; Chang et al., 2015; Kraus et al., 2013; Kristiansen et al., 2009). Blood pressure seems to be more strongly affected by chronic exposure, while heart rate changes reflect more acute effects and HRV may reflect both chronic and acute exposure to noise. Further research is necessary to better identify links between short-term effect of noise exposure on cardiovascular reactivity identifiable in experimental studies and long-term health-related changes associated

Please cite this article in press as: Francis, A.L., Oliver, J., Psychophysiological measurement of affective responses during speech perception, Hearing Research (2018), https://doi.org/10.1016/j.heares.2018.07.007

with chronic environmental or occupational noise exposure identifiable through epidemiological studies. In particular, noise stress may be the paradigmatic case in which the individual's specific emotional categorization of environmentally conditioned physiological effects plays a significant role in determining whether the immediate physiological response to noise exposure affects long-term cardiovascular health.

3.4. Facial electromyography

While all of the autonomic measures discussed thus far have been associated primarily with cognitive demand and/or affective arousal, facial electromyography (EMG) is the predominant method for assessing affective valence. Two muscles of the face have been shown to be of particular interest for the study of affect: the zygomaticus major and the corrugator supercillii. The zygomaticus is often called the “smile muscle” and serves to pull the corners of the lips upward and laterally, toward the zygomatic arch or cheekbone. The corrugator, sometimes termed the “frown muscle” is a small muscle located medially in the face, just above each eyebrow. It serves to furrow or wrinkle the center of the brow, pulling the eyebrows together. Although this response may occur in bright light to assist in shielding the eyes, its primary role seems to be related to emotion, especially negative emotions such as anger and discomfort (Larsen et al., 2003).

Facial muscle activation not only expresses emotion to others, but also appears to influence the sensation of emotion in the expressor (Neumann et al., 2005), and occurs even in the absence of visible changes in expression. Electrical activity in the zygomaticus tends to be higher in response to pleasant stimuli while corrugator activity is higher in response to unpleasant or negative stimuli (Potter and Bolls, 2012). However, it should be noted that, just as a smile may be evoked in response to certain kinds of unpleasant (or at least not explicitly pleasant) stimuli (e.g. a wry, pursed-lip grin expressing agreement with the statement of an unpleasant truth), assessment of genuine pleasure requires the additional measurement of activity in the orbicularis oculi at the lower edge of the eye socket. Simultaneous contraction of both zygomaticus major and orbicularis oculi has been termed the *Duchenne smile* (Ekman et al., 1990) and has been known as a valid indicator of pleasure since at least Darwin (1872). Therefore, if only one of these muscles is to be measured to assess emotional valence, it should probably be the corrugator, not the zygomaticus, as corrugator activation not only reliably indexes displeasure, but may also be reciprocally *relaxed* in response to pleasurable stimuli (Larsen et al., 2003; Potter and Bolls, 2012). In general, however, the accuracy of assessment of valence via facial EMG seems to improve with the inclusion of more, and more varied, arrays of muscles.

Activity in a number of other muscles has been studied with respect to emotional expression and stress while listening to speech or working in noise. For example, Mackersie and Cones (2011) recorded activity in the frontalis muscle, a large sheet-like muscle covering most of the forehead that, like the corrugator, is primarily involved in facial expression. It is superficial to the corrugator and larger in size, and thus surface EMG should be more sensitive to its activity than to corrugator. However, like the zygomaticus, frontalis is involved in a wide range of facial expressions associated with a wide variety of emotional valences, and thus may be less affectively specific than the corrugator. Nevertheless, Mackersie and Cones (2011) found a significant relationship between task difficulty in a dichotic digits task and frontalis activity, suggesting that task demands did differentially affect activity in this muscle. However, given the relationship between facial expression and emotion, especially between negative emotions and brow furrowing involving corrugator and frontalis, it is not possible to conclude that this frontalis activity necessarily reflects the application of cognitive effort as opposed to an affective response to the listening context.

In another study of speech perception in noise, Kristiansen et al. (2009) recorded trapezius muscle activity as an indicator of stress. The trapezius is a muscle in the upper back, and trapezius tension is often a contributor to stress-related back pain (Lundberg et al., 1994). Kristiansen et al. (2009) postulated that the stress of working in office noise might be reflected in greater tension in the trapezius due to “working in a posturally invariant manner.” Although they found significant increases in trapezius activity as a result of increasing workload, they did not observe an effect of or interaction with the presence of noise, possibly because their noise exposures were relatively short (35 min) compared to the durations that might be experienced during a typical work day in which trapezius tension might be expected. Thus, while facial muscle EMG likely represents the most direct physiological assessment of acute affective response to communication difficulties, the incorporation of other muscles into a test battery may be motivated by specific hypotheses about the affective consequences of particular study conditions but must be interpreted with care.

A final muscular response that could be of interest to studies of spoken communication is that of certain intrinsic and extrinsic muscles of the outer ear. These small muscles appear to represent a vestigial remnant of a system for directing the pinna toward sounds of interest, and for indicating some emotional responses similar to the pulling back of the ears by a dog or cat responding to a perceived threat (Hackley, 2015). Although humans and other apes no longer show significant voluntary or involuntary movements of the pinna, studies have shown that the transverse auricular muscle nevertheless shows increased activity in many people when the eyes are directed strongly to one side (Hackley, 2015). Similarly, the postauricular muscle exhibits a reflexive, bilateral increase in activity in response to loud sounds with sudden onsets (O'Beirne & Patuzzi, 1999). This postauricular (PA) reflex (PAR) is extremely fast, beginning within about 10 ms of the onset of the triggering sound, suggesting that it is a simple reflex similar to eye-blink measurements of startle. It is, however, highly resistant to habituation—thousands of responses can be evoked within an hour-long recording session (O'Beirne & Patuzzi, 1999). This suggests that the PAR is not simply a component of the typical startle reflex. There is also evidence that weak, but directionally specific, activity in the extrinsic and intrinsic ear muscles can be elicited by novel, salient, or task-relevant stimuli (Hackley, 2015). For example, although both PA muscles respond to acoustic transients, activity recorded in the muscle ipsilateral to a lateralized, novel stimulus (e.g. from a loudspeaker placed to the left of the listener) is stronger than that contralateral to the sound (Stekelenburg and Van Boxtel, 2002), though this may be related to eye movements (Wilson, 1908). Whether such activity in the auricular musculature reflects a true orienting response (see below), or merely an unusual reflex, remains to be determined (Hackley, 2015).

3.5. Endocrine and hormonal responses

A final class of physiological responses that may be significant for quantifying affective responses to communication in adverse environments are chemical in nature and are primarily associated with the concept of stress. We introduce this topic here in a more speculative fashion than even the previous discussions primarily because of the apparent link between chronic sympathetic nervous system arousal, the hypothalamic-pituitary-adrenal axis (HPA), and long-term, stress-related illness (Uchino et al., 2007), and also the possible link between stress-related illnesses such as heart disease and stroke with both hearing impairment and long-term noise

Please cite this article in press as: Francis, A.L., Oliver, J., Psychophysiological measurement of affective responses during speech perception, Hearing Research (2018), https://doi.org/10.1016/j.heares.2018.07.007

exposure(Fisher et al., 2014; Babisch, 2003; Bigert et al., 2005). Although there is currently little evidence to either support or refute the existence of such relationships, we believe that the topic is worthy of further study.

Stressors activate either or both the hypothalamic-pituitary-adrenal (HPA) and the sympathetic-adrenal-medullary (SAM) stress response systems. (Aston-Jones and Cohen, 2005). HPA activity is typically associated with psychological (especially psychosocial) stressors and feelings of lack of control (distress), while SAM (SNS) arousal is more closely associated with stressors that demand application of physical and/or cognitive effort (Dickerson and Kemeny, 2004; Skoluda et al., 2015). While the link between effort and distress is complex, it seems likely that it is influenced by individual differences in affective response to effort in a given context.

Effects of stress on the SAM system can be ascertained via measurements of responses from sympathetically innervated end organs. However, both the HPA and SAM systems ultimately affect activity in the adrenal glands, leading to wide-spread but not organ-specific distribution of catecholamines throughout the body. Circulating catacholamines are also associated with the presence of a variety of chemical markers in both blood and saliva. Chromogranin A is a protein involved in the secretion of catecholamines from cells in the adrenal medulla, and it may be measured in saliva as a marker for stress (including noise-induced stress) (Kanamaru et al., 2006; Kramer et al., 2016; Miyakawa et al., 2006). Other hormones secreted from adrenal cortex and associated with stress that may be found in saliva include cortisol and aldosterone. Cortisol appears to protect against or mitigate the effects of stress to some degree, but high concentrations of cortisol can also be harmful to health and are associated with a reduction in the size of the hippocampus (and concomitant loss of mnemonic capabilities), insomnia and possibly general negative affect (Wirth et al., 2011), and inhibition of immune system function (Uchino et al., 2007). Aldosterone participates in sodium metabolism, and chronically high concentrations of aldosterone due to stress may be associated with problems with blood pressure regulation (Kubzansky and Adler, 2010; Pratt, 2006; Ruilope and Tamargo, 2017). Therefore, salivary or blood chromogranin A, cortisol and/or aldosterone levels may represent an important link between momentary stress responses related to communication difficulties, consequently increased secretion of stress hormones from adrenal cortex, and the higher incidence of cardiovascular disease associated with hearing impairment (Fisher et al., 2014; Karpa et al., 2010) and long-term noise exposure (Babisch, 2011; Basner et al., 2015; Davies and Van Kamp, 2012; Lusk et al., 2002; Davies et al., 2005; van Kempen et al., 2002), though direct evidence for this hypothesis is not yet strong (Konkle et al., 2017).

Unfortunately, experimental evidence for such a relationship between short-term listening challenges and heightened endocrine response is mixed. Kramer et al. (2016) report the results of a preliminary study comparing salivary levels of cortisol and chromogranin A in listeners with hearing impairment and normally hearing listeners recognizing speech in noise. They observed a non-significant trend toward higher cortisol levels across conditions in listeners with hearing impairment as compared to normally hearing listeners, but no effect of condition. The only effect they observed on chromogranin A was a pattern of higher levels for the initial (pre-test) sample, suggesting that listeners were anticipating the difficulty of the task. Interestingly, chromogranin A levels tended to be lower in the hearing-impaired group, suggesting that they were perhaps not as anxious about the test as were the normally hearing listeners. Further research is clearly necessary to identify circumstances under which short-term noise- and communication-related stressors that may be investigated in the laboratory affect HPA axis activity, and how or whether repeated instances of such short-term events are related to the long-term health effects associated with chronic noise exposure and hearing impairment.

4. Summary and conclusions

In this review we have focused on providing a brief overview of a few important concepts and measurements that are useful in studies of psychophysiological responses to challenging listening conditions. Along the way, we have identified some themes that, together, provide a framework for guiding future research in this area. In particular, we have shown that different physiological responses, defined either in terms of whole systems (i.e. SNS vs. PSNS), individual end organs, or different measurements from a single end organ, show different degrees of correspondence to different sorts of psychological constructs. For example, electrodermal responses are closely associated with the construct of arousal, while facial electromyographic measurements tend to better reflect valence, and pupil dilation may be associated with a variety of both cognitive and affective constructs. However, each of these physiological systems also reflects influences from other psychological constructs, both cognitive and affective. Therefore, we have also emphasized the complexities and interrelatedness of the physiological systems in question. The SNS and PSNS do not function purely reciprocally, and even measurements taken from the same end organ may show directional fractionation, meaning that there are not likely to be many simple correspondences between single physiological measurements and individual psychological constructs. There is probably little insight to be gained from simply reporting effects of experimental manipulations on individual physiological variables. We have also identified the importance of individual differences in both psychological and physiological response especially with respect to the effects of aging. In this final section, we bring together these concerns to highlight some areas in which research on psychophysiological response to communicative challenges might most productively advance.

4.1. *Identifying consistent physiological indicators of affective response*

One important goal in psychophysiology is to identify patterns of physiological response that correspond consistently to specific psychological constructs. For example, the orienting reflex (OR) is a pattern of responses found across a broad range of psychophysiological measures (Barry, 2009) comprised of characteristic changes in primarily sympathetically innervated systems, including EDA and cardiovascular measures. The OR is often seen as a marker of the engagement of selective attention (Cohen, 2014). We suggest here that the OR represents the kind of complex, physiological construct with a clear connection to a comparatively well-defined psychological construct that might be usefully sought in research on affective responses to communicative challenges as well. Initially conceived of as a reflection of across-the-board increase in SNS arousal (Pavlov, 1927; Sokolov, 1963), more recent work suggests that the OR exhibits a subtler pattern of response fractionation, with different subsystems exhibiting different patterns of response with respect to stimulus intensity and repetition. For example, some component responses vary in strength with stimulus intensity, including skin conductance response (SCR) and capillary dilation/contraction (e.g. blood volume pulse amplitude, BVPA) and some decline with stimulus repetition (SCR), while others appear to remain consistent across stimulus intensity and repetition (heart rate deceleration) (Barry, 2009). Bradley (2009) has argued that these different components of the response may reflect different sub-processes associated with fulfilling distinct ecological demands: cardiac deceleration reflects preparation of systems for increasing intake of information while changes in skin conductance reflect simultaneous activation of systems for preparing for physical action. Both cardiac deceleration and increased skin conductance thus constitute significant physiological measures of a defined psychological construct (selective attention). However, in the context of a novel auditory stimulus (for example) both are best understood in combination with one another as components of the OR rather than alone. The OR has been found across many types of stimuli, so it appears to be relatively context-general, making it a good candidate for an *invariant* psychophysiological relationship in the terminology proposed by Richter and Slade (2017). On the other hand, the observation that the description of the relationship is improved by included some reference to the environmental/stimulus context suggests that the relationship is, strictly speaking, more like a marker than an invariant in the strictest sense.

In the same way, we propose that similar multi-system patterns of physiological response might ultimately serve as *markers* (context-specific) or even *invariants* of specific affective responses, and we propose that there is a need for research to identify such patterns. Care must be taken, of course, to avoid identifying spurious correspondences between end-organ behaviors that result from the complex neurophysiology of the ANS. For example, long-lasting arousal of multiple SNS-innervated end-organs could represent a consistent affective marker of a particular psychological state, or could represent broader activation of adrenergic neurons across multiple organs via blood-born catecholamines. Similarly, the fact that experimental manipulations designed to increase cognitive demand may have affective consequences and vice versa suggests a strong need to establish experimental paradigms that vary each candidate psychological construct (whether cognitive or affective) with as much independence from others as possible. Thus, considerable work is also still necessary to better specify the nature of the *psychological* constructs to which any identified physiological patterns might be related. Although we have presented arousal and valence as if they were well-established and unitary constructs, researchers pursuing constructionist theories of emotion have also begun to show that even as simple a phenomenon as arousal may not actually be a unitary construct at all (Satpute et al., 2018), and cognitive constructs such as effort and motivation suffer from even vaguer definitions (McGarrigle et al., 2014; Strand et al., 2018).

From a theoretical perspective, it is important that these hypothetical affective constructs are not intended to be isomorphic with canonical emotions. Rather, as with the correspondence between the physiological construct of the orienting reflex and the psychological construct of engagement of selective attention, we suggest that the kind of physiological construct we are proposing to search for will most likely be found in specifically defined sorts of psychological conditions such as time pressure or psychosocial threat, or in specific sorts of emotional conditions such as when communication becomes frustrating or when background noise becomes threatening. Ultimately, such increased precision in the specification of psychological constructs may blur or eliminate the distinction between cognitive and affective constructs (Barrett and Satpute, 2013).

4.2. Identifying individual differences and the trait-cognition-affect loop

In the literature on emotion, there is considerable evidence suggesting that personality traits interact with visceral responses to stimulation such that individuals with different patterns of personality traits show different patterns of emotional and autonomic responses in different conditions (Stemmler and Wacker, 2010). In our lab we are particularly interested in the trait of noise sensitivity. Noise sensitivity may be associated with a range of more basic personality traits (Shepherd et al., 2010), but appears to be a relatively clearly identifiable personality characteristic in its own right (Shepherd et al., 2016). It is present in roughly 20–40% of individuals (Shepherd et al., 2015), but is also associated with a variety of chronic clinical conditions, including autism and traumatic brain injury (Dischinger et al., 2009; Landon et al., 2012; Stiegler and Davis, 2010). Noise-sensitive individuals appear to have normal auditory acuity (Ellermeier et al., 2001) but are more likely to have poor health-related quality of life (Shepherd et al., 2010) and to miss work, especially if they have complex, mentally-demanding jobs (Fried et al., 2002). Noise sensitive people also experience greater interference with job performance from workplace noise, especially when performing mentally demanding tasks (Belojević et al., 1992), and find working in noise more annoying and more mentally straining than do less noise-sensitive people (Sandrock et al., 2009). Research by Shepherd and colleagues (Shepherd et al. 2015, 2016) suggests that individual differences in noise sensitivity reflect differences in physiological responsivity, but they may also be representative of a more generally negative emotional perspective (Shepherd et al., 2015). Research on behavioral sensitivity to noise levels when listening to speech in noise (e.g. as ascertained by the acceptable noise level test, Nabelek, et al., 1991; Taylor, 2008) suggests that there are also individual differences in this domain, and these may be related to hearing aid satisfaction (Nabelek et al., 2004). Further research is necessary to determine how individual differences in psychological and physiological traits relate to individual differences in affectively driven decisions such as abandoning a hearing aid or consistently using hearing protection devices.

4.3. Relating short-term autonomic responses to long-term health

Taking a multisystem approach to investigating psychophysiological responses to communication challenges may also enable future research connecting physiological responses to short-term challenges with epidemiological data regarding long-term health problems related to hearing impairment and chronic noise exposure. We have documented here the various ways in which adverse listening conditions have been shown to affect autonomic nervous system arousal. Chronic, repeated activation of allostatic systems (systems that respond to stressors to return physiological functions to homeostasis such as the autonomic nervous system) produces wear and tear on systems vital to health, especially immune and cardiovascular systems (McEwen, 1998), plausibly through the effects of increased cortisol levels (Uchino et al., 2007; Kaltsas and Chrousos, 2007). This allostatic overload is associated with many health problems, including greater likelihood of heart attack and stroke, increased incidence of depression, and possibly greater risk of dementia (Seeman et al., 2001), all of which are observed in the hearing-impaired population (Deal et al., 2017; Fisher et al., 2014; Lin et al., 2013; Lin and Albert, 2014) and are also associated with chronic noise exposure (Babisch, 2011; Basner et al., 2014; Stansfeld and Matheson, 2003).

Epidemiological studies suggest that individuals with hearing loss and those who work in noise experience greater levels of stress indicated by higher levels of salivary cortisol compared to those with normal hearing (Fisher et al., 2014) and/or who work in quiet (Babisch, 2003; Bigert et al., 2005; though cf. Stokholm et al., 2014 for a rigorous failure to confirm such a link). Acute noise exposure does increase HPA axis arousal (Evans et al., 1995) and cortisol

Please cite this article in press as: Francis, A.L., Oliver, J., Psychophysiological measurement of affective responses during speech perception, Hearing Research (2018), https://doi.org/10.1016/j.heares.2018.07.007

secretion (Fouladi et al., 2012) though exposure to lower levels such as may be found in a typical open-plan office may or may not affect cortisol levels (see review by Bigert et al., 2005; also Jahncke et al., 2011; Kristiansen et al., 2009). Furthermore, long-term effects of hearing impairment on the endocrine system may also be related to the greater psychosocial stress faced by hearing impaired listeners in a wide range of communicative contexts (Pichora-Fuller, 2016), given that psychosocial stress is also a strong inducer of HPA-axis arousal (Skoluda et al., 2015). Such issues have recently begun to receive more attention (Pichora-Fuller, 2016), especially as they relate to the concept of fatigue (see discussion by Hornsby et al., 2016). However, individuals differ in terms of their physiological and emotional responses to stress, and there is a complex interrelationship between stress, emotion, and personality traits. Thus, further research is clearly necessary to disentangle the complex relationship between environmental exposure to stressors, personality traits, and individual differences in psychophysiological reactivity.

Acknowledgements

This line of research was inspired by having attended the third conference on Aging and Speech Communication in Bloomington, IN. in 2009, and was enabled by a grant from the office of the EVPRP at Purdue University to support a year-long study in a second discipline (psychophysiology) in 2014–2015 and by funding from the office of the Provost at Purdue University. I am grateful to the many colleagues who have supported the development of my interest in this field through insightful discussions and encouraging comments over the past few years: Chris Weber, Ann Smith and Bridget Walsh; Rob Potter, Annie Lang and Sharon Mayell; Daniel Strauss; Adriana Zekveld, Sophia Kramer, Thomas Koelewijn; Matt Winn, Greg Norman; Phil Cusimano, Mickey Rowe, and Ken Graap. We are also grateful to those colleagues who have provided helpful feedback on various stages of this manuscript, especially Steven Hackley, Keith Kluender, Mark Sayles, Nicole Wetzel and two anonymous reviewers.

References

Andreassi, J.L., 2007. Psychophysiology: Human Behavior & Physiological Response, fifth ed. Psychology Press.

Aston-Jones, G., Cohen, J.D., 2005. An integrative theory of locus coeruleus-norepinephrine function: adaptive gain and optimal performance. Annu. Rev. Neurosci. 28, 403–450.

Babisch, W., 2003. Stress hormones in the research on cardiovascular effects of noise. Noise Health 5 (18), 1–11.

Babisch, W., 2011. Cardiovascular effects of noise. Noise Health 13 (52), 201–204.

Bandyopadhyay, D.D., Pammi, V.S.C., Srinivasan, N., 2013. Role of affect in decision making. Prog. Brain Res. 202, 37–53.

Barrett, L.F., 2017a. The theory of constructed emotion: an active inference account of interoception and categorization. Soc. Cognit. Affect Neurosci. 12 (1), 1–23.

Barrett, L.F., 2017b. How Emotions Are Made: the Secret Life of the Brain. Houghton Mifflin Harcourt.

Barrett, L.F., Satpute, A.B., 2013. Lage-scale brain networks in affective and social neuroscience: towards an integrative functional architecture of the brain. Curr. Opin. Neurobiol. 23, 361–372.

Barrett, L.F., Simmons, W.K., 2015. Interoceptive predictions in the brain. Nat. Rev. Neurosci. 16 (7), 419–429.

Barry, R.J., 2009. Habituation of the orienting reflex and the development of preliminary process theory. Neurobiol. Learn. Mem. 92 (2), 235–242.

Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., Stansfeld, S., 2014. Auditory and non-auditory effects of noise on health. Lancet 383 (9925), 1325–1332.

Basner, M., Brink, M., Bristow, A., De Kluizenaar, Y., Finegold, L., Hong, J., Janssen, S.A., Klaeboe, R., Leroux, T., Liebl, A., Matsui, T., Schwela, D., Sliwinska-Kowalska, M., Sörqvist, P., 2015. ICBEN review of research on the biological effects of noise 2011-2014. Noise Health 17 (75), 57–82.

Baumeister, R.F., Vohs, K.D., Nathan DeWall, C., Zhang, L., 2007. How emotion shapes behavior: feedback, anticipation, and reflection, rather than direct causation. Pers. Soc. Psychol. Rev. 11 (2), 167–203.

Beatty, J., 1982. Task-evoked pupillary responses, processing load, and the structure of processing resources. Psychol. Bull. 91 (2), 276–292.

Bechara, A., 2004. The role of emotion in decision-making: evidence from neurological patients with orbitofrontal damage. Brain Cognit. 55 (1), 30–40.

O'Beirne, G.A., Patuzzi, R.B., 1999. Basic properties of the sound-evoked post-auricular muscle response (PAMR). Hear. Res. 138 (1), 115–132.

Belojević, G., Öhrström, E., Rylander, R., 1992. Effects of noise on mental performance with regard to subjective noise sensitivity. Int. Arch. Occup. Environ. Health 64 (4), 293–301.

Belojević, G., Jakovljevic, B., Slepcevic, V., 2003. Noise and mental performance: personality attributes and noise sensitivity. Noise Health 6 (21), 77–89.

Berntson, G.G., Cacioppo, J.T., 2007. Integrative physiology: homeostasis, allostasis and the orchestration of systemic physiology. In: Cacioppo, J.T., Tassinary, L.G., Berntson, G.G. (Eds.), Handbook of Psychophysiology, third ed. Cambridge University Press, pp. 433–452.

Berntson, G.G., Cacioppo, J.T., Quigley, K.S., 1991. Autonomic determinism: the modes of autonomic control, the doctrine of autonomic space, and the laws of autonomic constraint. Psychol. Rev. 98 (4), 459–487.

Berntson, G.G., Cacioppo, J.T., Quigley, K.S., 1993. Respiratory sinus arrhythmia: autonomic origins, physiological mechanisms, and psychophysiological implications. Psychophysiology 30, 183–196.

Berntson, G.G., Cacioppo, J.T., Binkley, P.F., Uchino, B.N., Quigley, K.S., Fieldstone, A., 1994a. Autonomic cardiac control. III. Psychological stress and cardiac response in autonomic space as revealed by pharmacological blockades. Psychophysiology 31 (6), 599–608.

Berntson, G.G., Cacioppo, J.T., Quigley, K.S., 1994b. Autonomic cardiac control. I. Estimation and validation from pharmacological blockades. Psychophysiology 31 (6), 572–585.

Berntson, G.G., Cacioppo, J.T., Quigley, K.S., 1995. The metrics of cardiac chronotropism: biometric perspectives. Psychophysiology 32 (2), 162–171.

Berntson, G.G., Lozano, D.L., Chen, Y.J., 2005. Filter properties of root mean square successive difference (RMSSD) for heart rate. Psychophysiology 42 (2), 246–252.

Berntson, G.G., Quigley, K.S., Lozano, D., 2007. Cardiovascular psychophysiology. In: Cacioppo, J.T., Tassinary, L.G., Berntson, G.G. (Eds.), Handbook of Psychopyhsiology, third ed., pp. 182–210.

Berntson, G.G., Quigley, K.S., Norman, G.J., Lozano, D.L., 2017. Cardiovascular psychophysiology. In: Cacioppo, J.T., Tassinary, L.G., Berntson, G.G. (Eds.), Handbook of Psychopyhsiology, fourth ed., pp. 183–216.

Berridge, C.W., Waterhouse, B.D., 2003. The locus coeruleus–noradrenergic system: modulation of behavioral state and state-dependent cognitive processes. Brain Res. Rev. 42 (1), 33–84.

Bigert, C., Bluhm, G., Theorell, T., 2005. Saliva cortisol–a new approach in noise research to study stress effects. Int. J. Hyg Environ. Health 208 (3), 227–230.

Bitsios, P., Prettyman, R., Szabadi, E., 1996. Changes in autonomic function with age: a study of pupillary kinetics in healthy young and old people. Age Ageing 25 (6), 432–438.

Boucsein, W., 1992. Electrodermal Activity. Springer.

Bradley, M.M., 2000. Emotion and motivation. In: Cacioppo, J.T., Tassinary, L.G., Berntson, G.G. (Eds.), Handbook of Psychophysiology, second ed., pp. 602–642.

Bradley, M.M., 2009. Natural selective attention: orienting and emotion. Psychophysiology 46 (1), 1–11.

Bradley, M.M., Lang, P.J., 1994. Measuring emotion: the self-assessment manikin and the semantic differential. J. Behav. Ther. Exp. Psychiatr. 25 (1), 49–59.

Bradley, M.M., Lang, P.J., 2000. Emotion and motivation. In: Cacioppo, J.T., Tassinary, L.G., Berntson, G.G. (Eds.), Handbook of Psychophysiology, *second ed.*, pp. 602–642.

Bradley, M.M., Miccoli, L., Escrig, M.A., Lang, P.J., 2008. The pupil as a measure of emotional arousal and autonomic activation. Psychophysiology 45 (4), 602–607.

Bradley, M.M., Sapigao, R.G., Lang, P.J., 2017. Sympathetic ANS modulation of pupil diameter in emotional scene perception: effects of hedonic content, brightness, and contrast. Psychophysiology 54 (10), 1419–1435.

Buijs, R.M., 2013. The autonomic nervous system: a balancing act. Handb. Clin. Neurol. 117, 1–11.

Cacioppo, J.T., Berntson, G.G., 1994. Relationship between attitudes and evaluative space: a critical review, with emphasis on the separability of positive and negative substrates. Psychol. Bull. 115 (3), 401.

Cacioppo, J.T., Tassinary, L.G., 1990. Inferring psychological significance from physiological signals. Am. Psychol. 45 (1), 16–28.

Cacioppo, J.T., Berntson, G.G., Klein, D.J., 1992. What is an emotion? The role of somatovisceral afference, with special emphasis on somatovisceral "illusions. Rev. Pers. Soc. Psychol. 14, 63–98.

Cacioppo, J.T., Berntson, G.G., Binkley, P.F., Quigley, K.S., Uchino, B.N., Fieldstone, A., 1994a. Autonomic cardiac control. II. Noninvasive indices and basal response as revealed by autonomic blockades. Psychophysiology 31 (6), 586–598.

Cacioppo, J.T., Uchino, B.N., Berntson, G.G., 1994b. Individual differences in the autonomic origins of heart rate reactivity: the psychometrics of respiratory sinus arrhythmia and preejection period. Psychophysiology 31 (4), 412–419.

Chang, T.-Y., Liu, C.-S., Hwang, B.-F., Hsieh, H.-H., Bao, B.-Y., Chen, C.-J., Wang, V.-S., Lai, J.-S., 2015. Acute effects of noise exposure on 24-h ambulatory blood pressure in hypertensive adults. J. Hypertens. 33 (3), 507–514.

Cohen, R.A., 2014. The orienting response: index of attention. In: Cohen, R.A. (Ed.), The Neuropsychology of Attention. Springer US, pp. 135–157.

Cowan, N., 2017. The many faces of working memory and short-term storage. Psychonomic Bull. Rev. 24 (4), 1158–1170.

Critchley, H.D., Eccles, J., Garfinkel, S.N., 2013. Interaction between cognition, emotion, and the autonomic nervous system. Handb. Clin. Neurol. 117, 59–77.

Cvijanović, N., Kechichian, P., Janse, K., Kohlrausch, A., 2017. Effects of noise on arousal in a speech communication setting. Speech Commun. 88, 127–136.

Darrow, C.W., 1933. Considerations for evaluating the galvanic skin reflex. Am. J. Psychiatr. 90 (2), 285–298.

Darwin, C., 1872. The Expression of Emotion in Man and Animals.

Davies, D.R., Krkovic, A., 1965. Skin-conductance, alpha-activity, and vigilance. Am. J. Psychol. 78 (2), 304–306.

Davies, H., Van Kamp, I., 2012. Noise and cardiovascular disease: a review of the literature 2008-2011. Noise Health 14 (61), 287.

Davies, H.W., Teschke, K., Kennedy, S.M., Hodgson, M.R., Hertzman, C., Demers, P.A., 2005. Occupational exposure to noise and mortality from acute myocardial infarction. Epidemiology 16 (1), 25–32.

Dawson, M.E., Schell, A.M., Filion, D.L., 2007. The electrodermal system. In: Cacioppo, J.T., Tassinary, L.G., Berntson, G.G. (Eds.), Handbook of Psychophysiology, *third ed.*, pp. 200–223.

De Meersman, R.E., 1993. Aging as a modulator of respiratory sinus arrhythmia. J. Gerontol. 48 (2), B74–B78.

Deal, J.A., Betz, J., Yaffe, K., Harris, T., Purchase-Helzner, E., Satterfield, S., Pratt, S., Govil, N., Simonsick, E.M., Lin, F.R., 2017. Hearing impairment and incident dementia and cognitive decline in older adults: the health ABC study. J. Gerontol.A 72 (5), 703–709.

Dickerson, S.S., Kemeny, M.E., 2004. Acute stressors and cortisol responses: a theoretical integration and synthesis of laboratory research. Psychol. Bull. 130 (3), 355–391.

Dischinger, P.C., Ryb, G.E., Kufera, J.A., Auman, K.M., 2009. Early predictors of postconcussive syndrome in a population of trauma patients with mild traumatic brain injury. J. Trauma. Acute. Care. Surg. 66 (2), 289–297.

Dolcos, F., LaBar, K.S., Cabeza, R., 2004. Dissociable effects of arousal and valence on prefrontal activity indexing emotional evaluation and subsequent memory: an event-related fMRI study. Neuroimage 23, 64–74.

Dorman, M.F., Spahr, A., Gifford, R.H., Cook, S., Zhang, T., Loiselle, L., Yost, W., Cardy, L., Whittingham, J., Schramm, D., 2012. Current research with cochlear implants at Arizona State University. J. Am. Acad. Audiol. 23 (6), 385–395.

Duncan, S., Barrett, L.F., 2007. Affect is a form of cognition: a neurobiological analysis. Cognit. Emot. 21 (6), 1184–1211.

Duschek, S., Muckenthaler, M., Werner, N., del Paso, G.A.R., 2009. Relationships between features of autonomic cardiovascular control and cognitive performance. Biol. Psychol. 81 (2), 110–117.

Eckert, M.A., Teubner-Rhodes, S., Vaden Jr., K.I., 2016. Is listening in noise worth it? The neurobiology of speech recognition in challenging listening conditions. Ear Hear. 37, 101S–110S.

Edelberg, R., 1973. Local electrical response of the skin to deformation. J. Appl. Physiol. 34 (3), 334–340.

Ekman, P., Davidson, R.J., Friesen, W.V., 1990. The Duchenne smile: emotional expression and brain physiology: II. J. Pers. Soc. Psychol. 58 (2), 342–353.

Ellermeier, W., Eigenstetter, M., Zimmer, K., 2001. Psychoacoustic correlates of individual noise sensitivity. J. Acoust. Soc. Am. 109 (4), 1464–1473.

Elliot, A.J., 2006. The hierarchical model of approach-avoidance motivation. Motiv. Emot. 30, 111–116.

Evans, G.W., Hygge, S., Bullinger, M., 1995. Chronic noise and psychological stress. Psychol. Sci. 6 (6), 333–338.

Fairclough, S.H., 2009. Fundamentals of physiological computing. Interact. Comput. 21 (1–2), 133–145.

Fairnie, J., Moore, B.C., Remington, A., 2016. Missing a trick: auditory load modulates conscious awareness in audition. J. Exp. Psychol. Hum. Percept. Perform. 42 (7), 930–938.

Fisher, D., Li, C.M., Chiu, M.S., Themann, C.L., Petersen, H., Jónasson, F., Jónasson, P.V., Sverrisdottir, J.E., Garcia, M., Harris, T.B., Launer, L., Eiriksdottir, g., Gudnason, V., Hoffman, H.J., Cotch, M.F., 2014. Impairments in hearing and vision impact on mortality in older people: the AGES-Reykjavik Study. Age Ageing 43 (1), 69–76.

Fouladi, D.B., Nassiri, P., Monazzam, E.M., Farahani, S., Hassanzadeh, G., Hoseini, M., 2012. Industrial noise exposure and salivary cortisol in blue collar industrial workers. Noise and Health 14 (59), 184–189.

Francis, A.L., 2010. Improved segregation of simultaneous talkers differentially affects perceptual and cognitive capacity demands for recognizing speech in competing speech. Atten. Percept. Psychophys. 72 (2), 501–516.

Francis, A.L., MacPherson, M.K., Chandrasekaran, B., Alvar, A.M., 2016. Autonomic nervous system responses during perception of masked speech may reflect constructs other than subjective listening effort. Front. Psychol. 7.

Fried, Y., Melamed, S., Ben-David, H.A., 2002. The joint effects of noise, job complexity, and gender on employee sickness absence: an exploratory study across 21 organizations—the CORDIS study. J. Occup. Organ. Psychol. 75 (2), 131–144.

Friedman, B.H., 2010. Feelings and the body: the Jamesian perspective on autonomic specificity of emotion. Biol. Psychol. 84 (3), 383–393.

García-León, A., del Paso, G.A.R., Robles, H., Vila, J., 2003. Relative effects of harassment, frustration, and task characteristics on cardiovascular reactivity. Int. J. Psychophysiol. 47 (2), 159–173.

Gendolla, G.H.E., Richter, M., 2010. Effort mobilization when the self is involved: some lessons from the cardiovascular system. Rev. Gen. Psychol. 14 (3), 212–226.

Gilzenrat, M.S., Nieuwenhuis, S., Jepma, M., Cohen, J.D., 2010. Pupil diameter tracks changes in control state predicted by the adaptive gain theory of locus coeruleus function. Cognit. Affect Behav. Neurosci. 10 (2), 252–269.

Goldinger, S.D., Papesh, M.H., 2012. Pupil dilation reflects the creation and retrieval of memories. Curr. Dir. Psychol. Sci. 21 (2), 90–95.

Goldstein, D.S., 2013. Differential responses of components of the autonomic nervous system. In: Bujis, R.M., Swaab, D.F. (Eds.), Handbook of Clinical Neurology, *3rd Series*, vol. 117. Elsevier, pp. 13–22.

Goldstein, H.S., Edelberg, R., 1997. A plethysmographic method for demonstrating the response specificity of the oral vascular bed. Psychophysiology 34 (1), 124–128.

Goldstein, D.S., Bentho, O., Park, M.Y., Sharabi, Y., 2011. Low-frequency power of heart rate variability is not a measure of cardiac sympathetic tone but may be a measure of modulation of cardiac autonomic outflows by baroreflexes. Exp. Physiol. 96 (12), 1255–1261.

Gomez, P., von Gunten, A., Danuser, B., 2016. Autonomic nervous system reactivity within the valence–arousal affective space: modulation by sex and age. Int. J. Psychophysiol. 109, 51–62.

Grossman, P., Van Beek, J., Wientjes, C., 1990. A comparison of three quantification methods for estimation of respiratory sinus arrhythmia. Psychophysiology 27 (6), 702–714.

Hackley, S.A., 2015. Evidence for a vestigial pinna-orienting system in humans. Psychophysiology 52 (10), 1263–1270.

Heathers, J.A., 2014. Everything Hertz: methodological issues in short-term frequency-domain HRV. Front. Physiol. 5, 1–15.

Hess, E.H., 1975. The role of pupil size in communication. Sci. Am. 233 (5), 110–119.

Hornsby, B.W., Naylor, G., Bess, F.H., 2016. A taxonomy of fatigue concepts and their relation to hearing loss. Ear Hear. 37, 136S–144S.

Iani, C., Gopher, D., Lavie, P., 2004. Effects of task difficulty and invested mental effort on peripheral vasoconstriction. Psychophysiology 41 (5), 789–798.

Jahncke, H., Hygge, S., Halin, N., Green, A.M., Dimberg, K., 2011. Open-plan office noise: cognitive performance and restoration. J. Environ. Psychol. 31 (4), 373–382.

Jennings, J.R., Allen, B., Gianaros, P.J., Thayer, J.F., Manuck, S.B., 2015. Focusing neurovisceral integration: cognition, heart rate variability, and cerebral blood flow. Psychophysiology 52 (2), 214–224.

Kahneman, D., 1973. Attention and Effort. Prentice-Hall, Englewood Cliffs, NJ.

Kahneman, D., Peavler, W.S., Onuska, L., 1968. Effects of verbalization and incentive on the pupil response to mental activity. Can. J. Psychol. Rev. Canad. Psychol. 22 (3), 186–196.

Kaltsas, G.A., Chrousos, G.P., 2007. The neuroendocrinology of stress. Hand. Psychophysiol. 3, 303–318.

Kanamaru, Y., Kikukawa, A., Shimamura, K., 2006. Salivary chromogranin-A as a marker of psychological stress during a cognitive test battery in humans. Stress 9 (3), 127–131.

Karpa, M.J., Gopinath, B., Beath, K., Rochtchina, E., Cumming, R.G., Wang, J.J., Mitchell, P., 2010. Associations between hearing impairment and mortality risk in older persons: the Blue Mountains Hearing Study. Ann. Epidemiol. 20 (6), 452–459.

Kjellberg, A., Landström, U.L.F., Tesarz, M., Söderberg, L., Akerlund, E., 1996. The effects of nonphysical noise characteristics, ongoing task and noise sensitivity on annoyance and distraction due to noise at work. J. Environ. Psychol. 16 (2), 123–136.

Klabunde, R., 2011. Cardiovascular Physiology Concepts. Lippincott Williams & Wilkins.

Koelewijn, T., Zekveld, A.A., Festen, J.M., Rönnberg, J., Kramer, S.E., 2012. Processing load induced by informational masking is related to linguistic abilities. Int. J. Otolaryngol. 2012, 1–11.

Koelewijn, T., Shinn-Cunningham, B.G., Zekveld, A.A., Kramer, S.E., 2014. The pupil response is sensitive to divided attention during speech processing. Hear. Res. 312, 114–120.

Konkle, A.T.M., Keith, S.e., McNamee, J.P., Michaud, D., 2017. Chronic noise exposure in the spontaneously hypertensive rat. Noise Health 19 (90), 213–221.

Kramer, S.E., Kapteyn, T.S., Festen, J.M., Kuik, D.J., 1997. Assessing aspects of auditory handicap by means of pupil dilatation. Audiology 36 (3), 155–164.

Kramer, S.E., Teunissen, C.E., Zekveld, A.A., 2016. Cortisol, chromogranin A, and pupillary responses evoked by speech recognition tasks in normally hearing and hard-of-hearing listeners: a pilot study. Ear Hear. 37, 126S–135S.

Kraus, U., Schneider, A., Breitner, S., Hampel, R., Rückerl, R., Pitz, M., et al., 2013. Individual daytime noise exposure during routine activities and heart rate variability in adults: a repeated measures study. Environ. Health Perspect. 121 (5), 607.

Kreibig, S.D., 2010. Autonomic nervous system activity in emotion: a review. Biol. Psychol. 84 (3), 394–421.

Kristiansen, J., Mathiesen, L., Nielsen, P.K., Hansen, Å., Shibuya, H., Petersen, H.M., Lund, S.P., Skotte, J., Jørgensen, M.B., Søgaard, K., 2009. Stress reactions to cognitively demanding tasks and open-plan office noise. Int. Arch. Occup. Environ. Health. 82 (5), 631–641.

Kryter, K.D., 1959. Scaling human reactions to the sound from aircraft. J. Acoust. Soc. Am. 31 (11), 1415–1429.

Kryter, K.D., Poza, F., 1980. Effects of noise on some autonomic system activities. J. Acoust. Soc. Am. 67 (6), 2036–2044.

Kubzansky, L.D., Adler, G.K., 2010. Aldosterone: a forgotten mediator of the relationship between psychological stress and heart disease. Neurosci. Biobehav. Rev. 34 (1), 80–86.

Kuchinsky, S.E., Ahlstrom, J.B., Vaden, K.I., Cute, S.L., Humes, L.E., Dubno, J.R., Eckert, M.A., 2013. Pupil size varies with word listening and response selection difficulty in older adults with hearing loss. Psychophysiology 50 (1), 23–34.

Kuchinsky, S.E., Ahlstrom, J.B., Cute, S.L., Humes, L.E., Dubno, J.R., Eckert, M.A., 2014. Speech-perception training for older adults with hearing loss impacts word recognition and effort. Psychophysiology 51 (10), 1046–1057.

Kuchinsky, S.E., Dubno, J.R., Eckert, M.A., 2016a. Advances in quantifying listening effort: growth curve analyses of pupillometry data. J. Acoust. Soc. Am. 139 (4), 2101-2101.

Kuchinsky, S.E., Pandža, N.B., Haarmann, H.J., 2016b. Linking indices of tonic alertness: resting-state pupil dilation and cingulo-opercular neural activity. In: International Conference on Augmented Cognition. Springer International Publishing, pp. 218–230.

Kurzban, R., 2010. Does the brain consume additional glucose during self-control tasks? Evol. Psychol. 8 (2), 244–259.

Lacey, J.I., 1967. Somatic response patterning and stress: some revisions of activation theory. In: Appley, M.H., Trumbull, R. (Eds.), Psychological Stress: Issues in Research, pp. 14–38.

Lackner, H.K., Batzel, J.J., Rössler, A., Hinghofer-Szalkay, H., Papousek, I., 2014. Multi-time scale perspective in analyzing cardiovascular data. Physiol. Res. 63 (4), 439–456.

Landon, J., Shepherd, D., Stuart, S., Theadom, A., Freundlich, S., 2012. Hearing every footstep: noise sensitivity in individuals following traumatic brain injury. Neuropsychol. Rehabil. 22 (3), 391–407.

Lang, P.J., 2010. Emotion and motivation: toward consensus definitions and a common research purpose. Emotion. Rev. 2 (3), 229–233.

Lang, P.J., Bradley, M.M., 2010. Emotion and the motivational brain. Biol. Psychol. 84 (3), 437–450.

Larsen, J.T., Norris, C.J., Cacioppo, J.T., 2003. Effects of positive and negative affect on electromyographic activity over zygomaticus major and corrugator supercilii. Psychophysiology 40 (5), 776–785.

Lau, A.W., Edelstein, B.A., Larkin, K.T., 2001. Psychophysiological arousal in older adults: a critical review. Clin. Psychol. Rev. 21 (4), 609–630.

Lavie, N., 2010. Attention, distraction, and cognitive control under load. Curr. Dir. Psychol. Sci. 19 (3), 143–148.

Lemke, U., Besser, J., 2016. Cognitive load and listening effort: concepts and age-related considerations. Ear Hear. 37, 77S–84S.

Lin, F.R., Albert, M., 2014. Hearing loss and dementia–who is listening? Aging Ment. Health 18 (6), 671–673.

Lin, F.R., Yaffe, K., Xia, J., Xue, Q.L., Harris, T.B., Purchase-Helzner, E., Satterfield, S., Ayonayon, H.N., Ferrucci, L., Simonsick, E.M., 2013. Hearing loss and cognitive decline in older adults. JAMA Intern. Med 173 (4), 293–299.

Lundberg, U., Kadefors, R., Melin, B., Palmerud, G., Hassmén, P., Engström, M., Dohns, I.E., 1994. Psychophysiological stress and EMG activity of the trapezius muscle. Int. J. Behav. Med. 1 (4), 354–370.

Lusk, S.L., Hagerty, B.M., Gillespie, B., Caruso, C.C., 2002. Chronic effects of workplace noise on blood pressure and heart rate. Arch. Environ. Health 57 (4), 273–281.

Mackersie, C.L., Calderon-Moultrie, N., 2016. Autonomic nervous system reactivity during speech repetition tasks: heart rate variability and skin conductance. Ear Hear. 37, 118S–125S.

Mackersie, C.L., Cones, H., 2011. Subjective and psychophysiological indexes of listening effort in a competing-talker task. J. Am. Acad. Audiol. 22 (2), 113–122.

Mackersie, C.L., MacPhee, I.X., Heldt, E.W., 2015. Effects of hearing loss on heart-rate variability and skin conductance measured during sentence recognition in noise. Ear Hear. 36 (1), 145.

Matthen, M., 2016. Effort and displeasure in people who are hard of hearing. Ear Hear. 37, 28S–34S.

McCorry, L.K., 2007. Physiology of the autonomic nervous system. Am. J. Pharmaceut. Educ. 71 (4), 78.

McCoy, S.L., Tun, P.A., Cox, L.C., Colangelo, M., Stewart, R.A., Wingfield, A., 2005. Hearing loss and perceptual effort: downstream effects on older adults' memory for speech. Q. J. Exp. Psychol. Sect. A 58 (1), 22–33.

McEwen, B.S., 1998. Stress, adaptation, and disease: allostasis and allostatic load. Ann. N. Y. Acad. Sci. 840 (1), 33–44.

McGarrigle, R., Munro, K.J., Dawes, P., Stewart, A.J., Moore, D.R., Barry, J.G., Amitay, S., 2014. Listening effort and fatigue: what exactly are we measuring? A british society of audiology cognition in hearing special interest group 'white paper'. Int. J. Audiol. 53 (7), 433–445.

Mehler, B., Reimer, B., Coughlin, J.F., 2012. Sensitivity of physiological measures for detecting systematic variations in cognitive demand from a working memory task: an on-road study across three age groups. Hum. Factors 54 (3), 396–412.

Miyakawa, M., Matsui, T., Kishikawa, H., Murayama, R., Uchiyama, I., Itoh, T., Yoshida, T., 2006. Salivary chromogranin A as a measure of stress response to noise. Noise Health 8 (32), 108.

Molden, D.C., Hui, C.M., Scholer, A.A., Meier, B.P., Noreen, E.E., D'Agostino, P.R., Martin, V., 2012. Motivational versus metabolic effects of carbohydrates on self-control. Psychol. Sci. 23 (10), 1137–1144.

Murphy, P.R., O'connell, R.G., O'sullivan, M., Robertson, I.H., Balsters, J.H., 2014. Pupil diameter covaries with BOLD activity in human locus coeruleus. Hum. Brain Mapp. 35 (8), 4140–4154.

Nabelek, A.K., Tucker, F.M., Letowski, T.R., 1991. Toleration of background noises: relationship with patterns of hearing aid use by elderly persons. J. Speech Lang. Hear. Res. 34 (3), 679–685.

Nabelek, A.K., Tampas, J.W., Burchfield, S.B., 2004. Comparison of speech perception in background noise with acceptance of background noise in aided and unaided conditions. J. Speech Lang. Hear. Res. 47 (5), 1001–1011.

Neumann, R., Hess, M., Schulz, S.M., Alpers, G.W., 2005. Automatic behavioural responses to valence: evidence that facial action is facilitated by evaluative processing. Cognit. Emot. 19 (4), 499–513.

Newlin, D.B., Levenson, R.W., 1979. Pre-ejection period: measuring beta-adrenergic influences upon the heart. Psychophysiology 16, 546–553.

Norris, C.J., Gollan, J., Berntson, G.G., Cacioppo, J.T., 2010. The current status of research on the structure of evaluative space. Biol. Psychol. 84 (3), 422–436.

Oveis, C., Cohen, A.B., Gruber, J., Shiota, M.N., Haidt, J., Keltner, D., 2009. Resting respiratory sinus arrhythmia is associated with tonic positive emotionality. Emotion 9 (2), 265.

Parsons, R.J., 2007. Environmental psychophysiology. In: Cacioppo, J.T., Tassinary, L.G., Berntson, G.G. (Eds.), Handbook of Psychophysiology, *third ed.*, pp. 752–788.

Partala, T., Jokiniemi, M., Surakka, V., 2000. Pupillary responses to emotionally provocative stimuli. In: Proceedings of the 2000 Symposium on Eye Tracking Research & Applications. ACM, pp. 123–129.

Passchier-Vermeer, W., Passchier, W.F., 2000. Noise exposure and public health. Environ. Health Perspect. 108 (Suppl. 1), 123.

Pavlov, I.P., 1927. Conditioned Reflexes. An Investigation Of the Physiological Activity of the Cerebral Cortex.

Pichora-Fuller, M.K., 2016. How social psychological factors may modulate auditory and cognitive functioning during listening. Ear Hear. 37, 92S–100S.

Pichora-Fuller, M.K., Kramer, S.E., Eckert, M.A., Edwards, B., Hornsby, B.W., Humes, L.E., Lemke, U., Lunner, T., Matthen, M., Mackersie, C.L., Naylor, G., Phillips, N.A., Richter, M., Rudner, M., Sommers, M.S., Tremblay, K., Wingfield, A., 2016. Hearing impairment and cognitive energy: the framework for understanding effortful listening (FUEL). Ear Hear. 37, 5S–27S.

Picou, E.M., Ricketts, T.A., 2014. Increasing motivation changes subjective reports of listening effort and choice of coping strategy. Int. J. Audiol. 53 (6), 418–426.

Pierrette, M., Parizet, E., Chevret, P., Chatillon, J., 2015. Noise effect on comfort in open-space offices: development of an assessment questionnaire. Ergonomics 58 (1), 96–106.

Potter, R.F., Bolls, P., 2012. Psychophysiological Measurement and Meaning: Cognitive and Emotional Processing of Media. Routledge.

Pozzessere, G., Valle, E., Rossi, P., Petrucci, B., Ambrosini, A., D'Alessio, M., Pierelli, F., Giacomini, P., 1996. Pupillometric evaluation and analysis of light reflex in healthy subjects as a tool to study autonomic nervous system changes with aging. Aging Clin. Exp. Res. 8 (1), 55–60.

Pratt, J.H., 2006. The adrenergic nervous system conversing with the adrenal cortex. Hypertension 48 (5), 820–821.

Quintana, D.S., Alvares, G.A., Heathers, J.A.J., 2016. Guidelines for Reporting Articles on Psychiatry and Heart rate variability (GRAPH): recommendations to advance research communication. Transl. Psychiatry 6 (5) e803 1-10.

Richter, M., 2016. The moderating effect of success importance on the relationship between listening demand and listening effort. Ear Hear. 37, 111S–117S.

Richter, M., Slade, K., 2017. Interpretation of physiological indicators of motivation: caveats and recommendations. Int. J. Psychophysiol. 119, 4–10.

Ruilope, L.M., Tamargo, J., 2017. Aldosterone a relevant factor in the beginning and evolution of arterial hypertension. Am. J. Hypertens. 30 (5), 468–469.

Rylander, R., 2004. Physiological aspects of noise-induced stress and annoyance. J. Sound Vib. 277 (3), 471–478.

Samuels, E.R., Szabadi, E., 2008. Functional neuroanatomy of the noradrenergic locus coeruleus: its roles in the regulation of arousal and autonomic function part I: principles of functional organisation. Curr. Neuropharmacol. 6 (3), 235–253.

Sandrock, S., Schütte, M., Griefahn, B., 2009. Impairing effects of noise in high and low noise sensitive persons working on different mental tasks. Int. Arch. Occup. Environ. Health 82 (6), 779.

Satpute, A.B., Kragel, P.A., Barrett, L.F., Wager, T.D., Bianciardi, M., 2018. Deconstructing arousal into wakeful, autonomic and affective varieties. Neurosci. Lett. https://doi.org/10.1016/j.neulet.2018.01.042.

Schulz, A., Vögele, C., 2015. Interoception and stress. Front. Psychol. 6, 993.

Seeman, S., Sims, R., 2015. Comparison of psychophysiological and dual-task measures of listening effort. J. Speech Lang. Hear. Res. 58 (6), 1781–1792.

Seeman, T.E., Lusignolo, T.M., Albert, M., Berkman, L., 2001. Social relationships, social support, and patterns of cognitive aging in healthy, high-functioning older adults: MacArthur studies of successful aging. Health Psychol. 20 (4), 243.

Seth, A.K., Friston, K.J., 2016. Active interoceptive inference and the emotional brain. Phil. Trans. R. Soc. B 371 (1708), 20160007.

Shaffer, F., McCraty, R., Zerr, C.L., 2014. A healthy heart is not a metronome: an integrative review of the heart's anatomy and heart rate variability. Front. Psychol. 5, 1040.

Shepherd, D., Welch, D., Dirks, K.N., Mathews, R., 2010. Exploring the relationship between noise sensitivity, annoyance and health-related quality of life in a sample of adults exposed to environmental noise. Int. J. Environ. Res. Publ. Health 7 (10), 3579–3594.

Shepherd, D., Heinonen-Guzejev, M., Hautus, M.J., Heikkilä, K., 2015. Elucidating the relationship between noise sensitivity and personality. Noise Health 17 (76), 165.

Shepherd, D., Hautus, M.J., Lee, J., Mulgrave, J., 2016. Electrophysiological approaches to noise sensitivity. J. Clin. Exp. Neuropsychol. 38 (8), 900–912.

Siegel, E.H., Sands, M.K., Van den Noortgate, W., Condon, P., Chang, Y., Dy, J., Quigley, K.S., Barrett, L.F., 2018. Emotion fingerprints or emotion populations? A meta-analytic investigation of autonomic features of emotion categories. Psychol. Bull. 144 (4), 343–393.

Skoluda, N., Strahler, J., Schlotz, W., Niederberger, L., Marques, S., Fischer, S., Thoma, M.V., Spoerri, c., Ehlert, U., Nater, U.M., 2015. Intra-individual psychological and physiological responses to acute laboratory stressors of different intensity. Psychoneuroendocrinology 51, 227–236.

Sokolov, E.N., 1963. Perception and the Conditioned Reflex.

Stansfeld, S.A., Matheson, M.P., 2003. Noise pollution: non-auditory effects on health. Br. Med. Bull. 68 (1), 243–257.

Steinhauer, S.R., Siegle, G.J., Condray, R., Pless, M., 2004. Sympathetic and parasympathetic innervation of pupillary dilation during sustained processing. Int. J. Psychophysiol. 52 (1), 77–86.

Stekelenburg, J.J., Van Boxtel, A., 2002. Pericranial muscular, respiratory, and heart rate components of the orienting response. Psychophysiology 39 (6), 707–722.

Stemmler, G., 2004. Physiological processes during emotion. In: Philippot, P., Feldman, R.S. (Eds.), The Regulation of Emotion. Lawrence Erlbaum Associates, pp. 35–72.

Stemmler, G., Wacker, J., 2010. Personality, emotion, and individual differences in physiological responses. Biol. Psychol. 84 (3), 541–551.

Stephens, C.L., Christie, I.C., Friedman, B.H., 2010. Autonomic specificity of basic emotions: evidence from pattern classification and cluster analysis. Biol. Psychol. 84 (3), 463–473.

Stiegler, L.N., Davis, R., 2010. Understanding sound sensitivity in individuals with autism spectrum disorders. Focus. Autism. Other. Dev. Disabil. 25 (2), 67–75.

Stokholm, Z.A., Hansen, Å.M., Grynderup, M.B., Bonde, J.P., Christensen, K.L., Frederiksen, T.W., Lund, S.P., Vestergaard, J.M., Kolstad, H.A., 2014. Recent and long-term occupational noise exposure and salivary cortisol level. Psychoneuroendocrinology 39, 21–32.

Strand, J.F., Brown, V.A., Merchant, M.B., Brown, H.E., Smith, J., 2018. Measuring listening effort: convergent validity, sensitivity, and lingks with cognitive and personality measures. J. Speech Lang. Hear. Res. 61, 1463–1486.

Strauss, D.J., Francis, A.L., 2017. Toward a taxonomic model of attention in effortful listening. Cognit. Affect Behav. Neurosci. 1–17.

Styliadis, C., Ioannides, A.A., Bamidis, P.D., Papadelis, C., 2015. Distinct cerebellar lobules process arousal, valence and their interaction in parallel following a temporal hierarchy. Neuroimage 110, 149–161.

Surprenant, A.M., 2007. Effects of noise on identification and serial recall of nonsense syllables in older and younger adults. Aging Neuropsychol. Cognit. 14 (2), 126–143.

Taylor, B., 2008. The Acceptable Noise Level Test as a predictor of real-world hearing aid benefit. Hear. J. 61 (9), 39–40.

Thayer, J.F., Hansen, A.L., Saus-Rose, E., Johnsen, B.H., 2009. Heart rate variability, prefrontal neural function, and cognitive performance: the neurovisceral integration perspective on self-regulation, adaptation, and health. Ann. Behav. Med. 37 (2), 141–153.

Tulen, J.H.M., Moleman, P., Van Steenis, H.G., Boomsma, F., 1989. Characterization of stress reactions to the Stroop color word test. Pharmacol. Biochem. Behav. 32 (1), 9–15.

Tun, P.A., McCoy, S., Wingfield, A., 2009. Aging, hearing acuity, and the attentional costs of effortful listening. Psychol. Aging 24 (3), 761.

Uchino, B.N., Smith, T.W., Holt-Lunstad, J., Campo, R., Reblin, M., 2007. Stress and illness. In: Cacioppo, J.T., Tassinary, L.G., Berntson, G.G. (Eds.), Handbook of Psychophysiology, third ed., pp. 608–664.

Van Kempen, E.E., Kruize, H., Boshuizen, H.C., Ameling, C.B., Staatsen, B.A., de Hollander, A.E., 2002. The association between noise exposure and blood pressure and ischemic heart disease: a meta-analysis. Environ. Health Perspect. 110 (3), 307.

Wehrwein, E.A., Orer, H.S., Barman, S.M., 2016. Overview of the anatomy, physiology, and pharmacology of the autonomic nervous system. Compr. Physiol. 6, 1239–1278.

Wetzel, N., Buttelmann, D., Schieler, A., Widmann, A., 2016. Infant and adult pupil dilation in response to unexpected sounds. Dev. Psychobiol. 58 (3), 382–392.

World Health Organization (WHO), Joint Research Centre of the Commission, 2011. Report on “Burden of Disease from Environmental Noise”.

Widmann, A., Schröger, E., Wetzel, N., 2017. Emotional arousal in novelty processing is indicated by the P3a and by the sympathetic component of the pupil dilation response. Psychophysiology 54 (Suppl. 1), S73.

Wiens, S., 2005. Interoception in emotional experience. Curr. Opin. Neurol. 18 (4), 442–447.

Wierda, S.M., van Rijn, H., Taatgen, N.A., Martens, S., 2012. Pupil dilation deconvolution reveals the dynamics of attention at high temporal resolution. Proc. Natl. Acad. Sci. Unit. States Am. 109 (22), 8456–8460.

Wilcott, R.C., 1967. Arousal sweating and electrodermal phenomena. Psychol. Bull. 67 (1), 58.

Wilson, R.C., 1908. A new indication for operation in otitis media suppurativa. J. Roy. Army Med. Corps 11 (1), 58–63.

Wingfield, A., 2016. Evolution of models of working memory and cognitive resources. Ear Hear. 37, 35S–43S.

Winn, M.B., 2016. Rapid release from listening effort resulting from semantic context, and effects of spectral degradation and cochlear implants. Trends in Hear 20, 1–17.

Winn, M.B., Edwards, J.R., Litovsky, R.Y., 2015. The impact of auditory spectral resolution on listening effort revealed by pupil dilation. Ear Hear. 36 (4), e153.

Wirth, M.M., Scherer, S.M., Hoks, R.M., Abercrombie, H.C., 2011. The effect of cortisol on emotional responses depends on order of cortisol and placebo administration in a within-subject design. Psychoneuroendocrinology 36 (7), 945–954.

Zekveld, A.A., Kramer, S.E., Festen, J.M., 2011. Cognitive load during speech perception in noise: the influence of age, hearing loss, and cognition on the pupil response. Ear Hear. 32 (4), 498–510.

Zekveld, A.A., Rudner, M., Kramer, S.E., Lyzenga, J., Rönnberg, J., 2014. Cognitive processing load during listening is reduced more by decreasing voice similarity than by increasing spatial separation between target and masker speech. Front. Neurosci. 8, 88.

Please cite this article in press as: Francis, A.L., Oliver, J., Psychophysiological measurement of affective responses during speech perception, Hearing Research (2018), https://doi.org/10.1016/j.heares.2018.07.007