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OVERVIEW

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# Listening effort: Are we measuring cognition or affect, or both?

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**Abstract**

Listening effort is increasingly recognized as a factor in communication, particularly for and with nonnative speakers, for the elderly, for individuals with hearing impairment and/or for those working in noise. However, as highlighted by McGarrigle et al., *International Journal of Audiology*, 2014, *53*, 433–445, the term "listening effort" encompasses a wide variety of concepts, including the engagement and control of multiple possibly distinct neural systems for information processing, and the affective response to the expenditure of those resources in a given context. Thus, experimental or clinical methods intended to objectively quantify listening effort may ultimately reflect a complex interaction between the operations of one or more of those information processing systems, and/or the affective and motivational response to the demand on those systems. Here we examine theoretical, behavioral, and psychophysiological factors related to resolving the question of what we are measuring, and why, when we measure "listening effort."

This article is categorized under:
- Linguistics > Language in Mind and Brain
- Psychology > Theory and Methods
- Psychology > Attention
- Psychology > Emotion and Motivation

KEYWORDS
affect, attention, listening effort, psychophysiology

## 1 | INTRODUCTION

The term "listening effort" is increasingly common in speech, language, and hearing research, and effort is increasingly acknowledged to play a vital role in listeners' communicative behavior. The feeling that listening is too effortful may lead to tuning out of a conversation, abandoning a hearing aid, or choosing not to attend a social event in a noisy venue (McGarrigle et al., 2014; Ohlenforst et al., 2017; Peelle, 2018). Expending effort in listening may increase stress and fatigue and through these have long-term consequences for mental and physical health (Hornsby, 2013; Kramer, Kapteyn, Kuik, & Deeg, 2002; Pichora-Fuller, 2016; Wang et al., 2018). But what, exactly do we mean by the term "effort" in respect to listening? Although McGarrigle and colleagues raised this question in 2014, and Pichora-Fuller and colleagues proposed a definition in 2016, some basic questions still remain: What makes listening effortful? How can we measure it, and what might these measures tell us about the consequences of effortful listening?

In this overview article we begin with the distinction between the effort that is demanded by the acoustic and cognitive complexity of a listening situation (demanded effort) and the effort that a listener actually exerts to listen in that situation (exerted effort). To this we propose adding the feelings that a listener has about how much effort is being spent (assessed effort) (as shown schematically in Figure 1). While this addition is proposed here a priori, we have previously argued for the importance of a sense of how one is performing and a determination of whether it is worth the effort in the context of a proposed computational model of listening effort (Schneider, Bernarding, Francis, Hornsby, & Strauss, 2019). These senses of the term "effort" are of course closely related, and are often treated as interchangeable. For example, researchers typically assume that experiment participants will exert as much effort as needed to accomplish a given task and no more, an assumption codified in *motivational intensity theory* (cf. discussion by Gendolla & Richter, 2010). The expectation is that listeners will devote sufficient resources to accomplish a given task *as long as the task is not perceived to be too difficult to accomplish*, and *as long as accomplishing the task continues to seem like a worthwhile goal*. Thus, as long as the perceived difficulty and benefits of carrying out the task do not change too much, changing the complexity of the task is considered one way to potentiate the degree of effort exerted, making it seemingly simple to assume that exerted effort can be quantified as a function of task difficulty.

However, there are two potential complications with equating task difficulty (demanded effort) and exerted effort. First, there is a certain circularity to such arguments (Navon, 1984;see van der Wal & van Steenbergen, 2018 for a recent discussion) in the sense that task performance seems often to be treated both as an independent factor related to effort (this task is more effortful because people perform worse on it), and as a dependent measure of the effort that participants devote to the task (people perform worse on this task because it is the more effortful one). Second, in some of the most relevant cases for studies of listening effort, factors other than task difficulty may affect participants' exerted effort, either by affecting their perception of task difficulty, or by affecting their sense of whether the goal is worthwhile or not. For example, fatigued listeners may decide that a given task requires more resources than it would seem to in an unfatigued state, as in the case in which physical fatigue causes observers to perceive hills as steeper, that is, more effortful to climb (Bhalla & Proffitt, 1999). Similarly, having performed a mentally fatiguing initial task makes people less likely to exert effort on subsequent mentally demanding tasks, though such fatigue-related effects may also vary depending on the participants' perception of goal importance (Wright, Patrick, Thomas, & Barreto, 2013). Thus, listeners in adverse conditions may also change their willingness to keep listening over time. The question of whether this is due to an actual loss of capability or due to a change in attitude or desire is not always determinable (see Hornsby, Naylor, & Bess, 2016 for discussion), but highlights the potential to distinguish between exerted effort and assessed effort. Finally, changes in incentives can also affect the assessment of how worthwhile it is to achieve a particular goal (Richter & Gendolla, 2009), and therefore how much effort to expend on it (Koelewijn, Zekveld, Lunner, & Kramer, 2018; Richter, 2016).

In summary, it seems reasonable to consider "listening effort" as a psychological phenomenon that must be at least to some extent independent of the demands of the task itself. Moreover, there seems to be some possibility of distinguishing between exerted effort and the affective or emotional response to how much effort has been or is being exerted. However, these two aspects of effort seem to be intrinsically related, as reflected especially in terms of the overlap between the neural systems and physiological measures associated with them, and it remains unclear whether it is possible to investigate them separately (see Pattyn, Van Cutsem, Dessy, & Mairesse, 2018). The goal of this overview article is to develop a better understanding of what it might mean to "exert listening effort" and then examine some methods used to quantify listening effort in order to set the

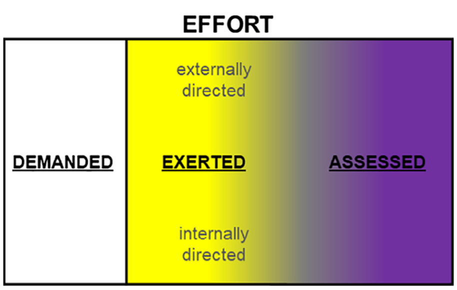


**FIGURE 1** A schematic illustration of the proposed clear distinction between demanded effort (associated with task properties) and the two less easily distinguished (hence fuzzily bounded) behaviorally or physiologically measurable properties of exerted and (self-)assessed effort. Demanded effort is quantifiable in terms of task properties such as SNR, number of competing talkers, memory load, degree of distortion of target speech, and so forth. Exerted and assessed effort are typically quantified using the behavioral and physiological measures discussed in the text. We also indicate a proposed distinction between externally and internally directed cognitive resources and associated these both mainly with exerted effort because, while they are often distinguished theoretically (see text), they may or may not be distinguishable in terms of how listeners feel about (assess) the effort they are exerting. SNR, signal-to-noise ratios

stage for future research investigating the manner and extent of the relationship between exerted and assessed effort. We focus on measurements and physiological systems that have been identified as reflecting the engagement of cognitive mechanisms in response to listening demands, but then highlight ways in which many of these same measures are also associated with affective responses to emotionally evocative stimulation. In the final section, we argue that the extensive overlap between physiological systems associated with exerted listening effort and those associated with affective responses is central to the conceptualization of listening effort as a fundamentally affective as well as cognitive phenomenon.

## 2 | DEFINING LISTENING EFFORT

The "cost" of mental exertion has been considered in terms of resource expenditure from at least three major perspectives. Effort may be seen from an economic (or "neuroeconomic", see Eckert, Teubner-Rhodes, & Vaden, 2016) perspective as an "opportunity cost" that reflects the outcome of an implicit evaluation of the benefit of the alternative opportunities lost as a result of conducting a particular behavior (Kurzban, 2016; Kurzban, Duckworth, Kable, & Myers, 2013). From this perspective, more effortful tasks are those that are deemed less beneficial (i.e., have a poorer cost–benefit ratio) compared to other options. This perspective has the advantage of explicitly incorporating aspects of motivation (cf. Matthen, 2016; Richter, 2016), but it begs the question of how, exactly, relative cost or benefit is assessed internally. Other than time spent, what is the "cost" of (what is "spent" when) doing one task as compared to another?

From the perspective of decision theory and the study of *ego depletion* (Baumeister et al., 1998, 2008; see discussion by Johnson, 2008) it is possible that this question may be answerable in terms of the consumption of physiological resources (though note that the original conceptualization of ego depletion has been called into significant question by recent meta-analyses, for example, Friese, Loschelder, Gieseler, Frankenbach, & Inzlicht, 2019). Nevertheless, the exertion of cognitive effort may result in the depletion of material physiological resources such as blood glucose, astrocytic glycogen, oxygen, or neurotransmitters (Christie & Schrater, 2015; Fairclough & Houston, 2004; Westbrook & Braver, 2016) making the exertion of effort costly at a metabolic level. This perspective has the advantage of enabling very explicit predictions about measureable effects of experimental manipulations, and it is possible that, in the future, research in these areas will have advanced to a point where we can simply measure "effort" directly in terms of the consumption of specific metabolites. However, while glucose represents the most promising such metabolite at this point, it is important to note that there is conflicting evidence as to whether cognitively demanding behaviors change blood glucose levels to a measurable degree (Vadillo, Gold, & Osman, 2016; see Kurzban et al., 2013 for a review), and it seems likely that the role of glucose is more closely related to motivation than to resource capacity per se (Molden et al., 2012). Similarly, as we discuss below, the few studies of neurochemical measures related to listening effort thus far have also been inconclusive. Thus, for the moment at least, the most productive conceptualization of effort appears to be as the application of various abstract, limited-capacity psychological constructs such as working memory or selective attention, and it is this perspective that currently dominates the discussion of listening effort.

### 2.1 | Listening effort as allocation of cognitive resources

The most commonly discussed contexts that invoke the concept of listening effort is invoked include (a) understanding a speech signal that is distorted (Francis, MacPherson, Chandrasekaran, & Alvar, 2016; Francis & Nusbaum, 2009; Pals, Sarampalis, & Başkent, 2013; Ward, Shen, Souza, & Grieco-Calub, 2017; Winn, Edwards, & Litovsky, 2015), atypical (McAuliffe, Wilding, Rickard, & O'Beirne, 2012; Nagle & Eadie, 2012, 2018; Van Engen & Peelle, 2014; Whitehill & Wong, 2006), or masked or reverberant (Desjardins & Doherty, 2013; Gosselin & Gagné, 2011; Holube, Haeder, Imbery, & Weber, 2016; Picou, Gordon, & Ricketts, 2016; N. Rönnberg, Rudner, Lunner, & Stenfelt, 2014; Rudner, Lunner, Behrens, Thorén, & Rönnberg, 2012; Sarampalis, Kalluri, Edwards, & Hafter, 2009), or (b) listening while being distracted by competing information (Janse, 2012; Koelewijn, Zekveld, Festen, Rönnberg, & Kramer, 2012; Mackersie & Cones, 2011; Tun, O'Kane, & Wingfield, 2002), or (c) having to simultaneously hold and rehearse unrelated information in mind while listening (Francis, 2010; Rudner et al., 2012), see, for example, Mattys, Davis, Bradlow, and Scott (2012) and Peelle (2018) for reviews. In considering what these tasks might all share, we begin with a rephrasing of Pichora-Fuller et al.'s (2016) consensus definition of listening effort as *the allocation of cognitive resources to overcome obstacles or challenges to achieving listening-oriented goals*.

In most research, the *obstacles* that interfere with achieving listening tasks generally consist of factors that reduce speech intelligibility, whether that is hearing impairment (Pichora-Fuller et al., 2016; Shinn-Cunningham & Best, 2008), noise masking (Zekveld, Kramer, & Festen, 2011), listening in a second language (Borghini & Hazan, 2018; Francis, Tigchelaar, Zhang, & Zekveld, 2018), a talker's unfamiliar accent (Van Engen & Peelle, 2014), or other nonstandard phonetic properties of target speech (Francis et al., 2016; Nagle & Eadie, 2018; Winn et al., 2015). In addition, some work also considers challenges that arise in comprehension of or memory for the message (Piquado, Isaacowitz, & Wingfield, 2010; Wingfield, 2016). With respect to identifying which cognitive *resources* are allocated during tasks that incur listening effort, there is a relatively broad consensus that the primary cognitive resource in question tends to be working memory capacity and/or the allocation and use of attention (Heald & Nusbaum, 2014; Pichora-Fuller et al., 2016; Wingfield, 2016). Following the discussion of Strauss and Francis (2017), attention may be the resource most directly applicable to respond to the demands of listening (Chun, Golomb, & Turk-Browne, 2011; Song & Iverson, 2018; Strauss et al., 2010; Wild et al., 2012), though other related resources including working memory (Rudner et al., 2012; Wingfield, 2016) and executive function (Brännström, Karlsson, Waechter, & Kastberg, 2018; Perrone-Bertolotti, Tassin, & Meunier, 2017; Ward et al., 2017) surely play a role. These theoretical constructs are closely related, and the precise nature of their relationship is the subject of a huge scientific literature (Awh, Vogel, & Oh, 2006; Cowan, 1993; Engle, 2002; Fougnie, 2008; McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010), rendering it beyond the scope of this article to address in detail. Nevertheless, considering some ways in which cognitive resources, even broadly defined, are applied to overcome obstacles to speech understanding can inform the search for quantifiable behavioral or physiological correlates of listening effort.

## 2.2 | Models of resource allocation in speech perception

A thorough discussion of the role of effort in theories of speech perception would have to include a majority of theories that do not incorporate a consideration of resource demand, or only do so in a post-hoc sense. The interested reader is referred to Heald and Nusbaum (2014) for a review of this issue. Here, we discuss two recent classes of theories of speech perception that explicitly address the problem of resource allocation, highlighting similarities in their architectural characteristics that exemplify some of the major trends within the field.

Active models (Heald & Nusbaum, 2014) consider resource demand as an intrinsic property of the mechanism of speech perception. In such models, speech perception is conceptualized as an inherently closed-loop process, integrating feed-forward and feedback information flow. According to one such model, mental representations of the incoming speech signal are compared against the mental representations of plausible linguistic interpretations (hypothesis testing) and, crucially, the outcome of this comparison serves to adjust the processing of the incoming linguistic signal as well as hypotheses about what the linguistic content of the signal might be. Thus, when the signal is obscured or distorted, the distribution of selective attention must be adaptively adjusted to focus on signal properties that are either more robust or more accessible while more and alternative potential interpretations are brought from long-term memory into working memory storage for comparison. It is this cyclical, successive refinement process of shifting selective attention and generating and assessing alternative hypotheses (see Figure 2a) that incurs effort in the form of increasing demand on cognitive resources such as working memory and attention. According to this conceptualization, all speech perception demands some commitment of cognitive resources, but more challenging (more masked, more distorted) speech requires greater resource commitment.

The Ease of Language Understanding (ELU) model (J. Rönnberg et al., 2013) (Figure 2b) incorporates a similar feedback loop, although in this case the loop is assumed to be engaged only when there is insufficiently clear information in the incoming signal to afford a reliable match to long-term memory representations via a strictly feed-forward path. In this case, an explicit, capacity-demanding processing mechanism is engaged and thus gives rise to effortful listening (see also work by Kahneman & Egan, 2011 for a more general conceptualization of such a two-processing-systems theory). Initial versions of the ELU model did not directly address the possibility that top-down mechanisms might influence the earliest stages of auditory signal processing. However, in a modified version (Edwards, 2016) (Figure 2c), an early-occurring, resource-demanding stage of processing is introduced to account for the application of selective attention and other cognitive processes that contribute to auditory scene analysis. The introduction of this module is motivated by the same sorts of observations that motivate other active models such as that of Nusbaum and colleagues: when auditory signal quality is compromised, even when recognition of the linguistic message is ultimately successful, detrimental effects may still be observed at later stages of processing, such as message comprehension and long-term retention (McCoy et al., 2005; Murphy, O'Connell, O'Sullivan, Robertson, & Balsters, 2014; Pichora-Fuller & Souza, 2003; Rabbitt, 1968; Surprenant, 1999). By including a pathway through which top-down (resource-demanding) processes may affect these earlier stages of scene-analytic processing, the revised ELU model remains computationally an active mechanism (i.e., it incorporates a feedback loop). However, by distinguishing between resource demand at peripheral (perceptual) levels of processing versus more central (conceptual, linguistic) levels, this model can be more clearly related to conceptualizations of listening effort based in more general theories of the cognitive neuroscience of attention that distinguish between more externally directed versus internally directed resources (e.g., Shinn-Cunningham, 2008; Strauss & Francis, 2017).

## 2.3 | Early versus late stages of attentional demand

Both of these models are compatible with the standing tradition of distinguishing between the application of attention to early versus late (or perceptual vs. cognitive, or external vs. internal) processing (cf. reviews by Driver, 2001; Lavie, 2005). In the auditory literature, similar discussions have often appeared in the context of distinguishing between *energetic* and *informational* masking (Kidd & Colburn, 2017; Kidd, Mason, Richards, Gallun, & Durlach, 2008; see discussion explicitly relating these concepts to listening effort by Francis et al., 2016), though of course the two sorts of dichotomies are not entirely isomorphic. Shinn-Cunningham (2008) adapted theories of visual object recognition to develop a characterization of the role of attention in speech perception and audition more generally. As discussed in more detail by Strauss and Francis (2017),

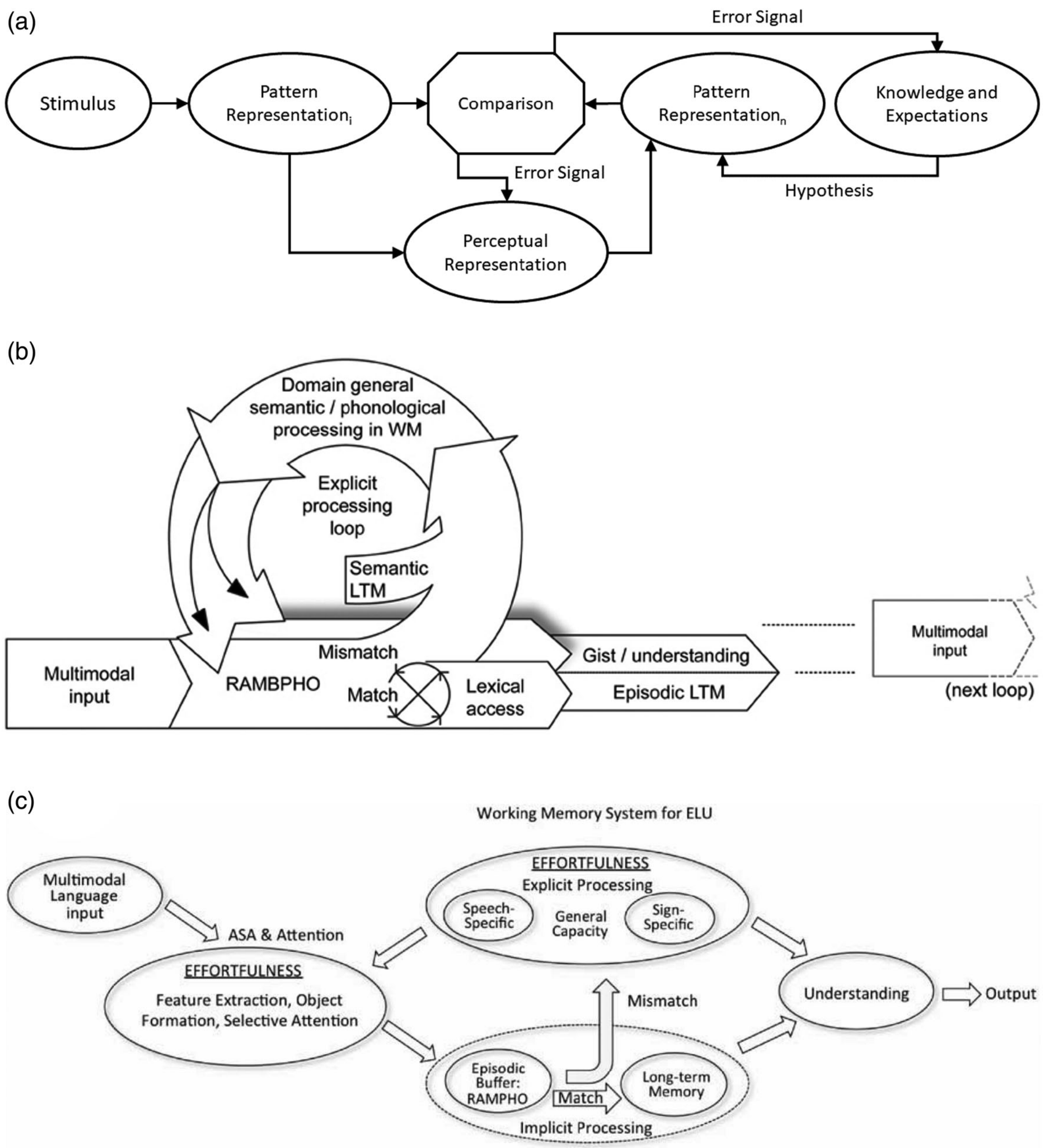


**FIGURE 2** Legend on next page.

Shinn-Cunningham distinguishes between processes of *object formation*, *object selection*, and *coping mechanisms* such as "filling in" and "recalling from memory." In terms of Edwards' (2016) revised ELU model, these processes can be assigned roughly to the auditory scene analysis stage (object formation and selection) and the explicit processing stage (recalling from memory), with "filling in" possibly represented by top-down adjustment of low-level (i.e., object formation) processes. Strauss and Francis (2017) make a similar binary distinction between externally and internally directed attention, again roughly corresponding respectively to the earlier- and later-occurring resource-demanding processes depicted in the extended ELU model.

This binary distinction between externally and internally directed attentional mechanisms is also pervasive in theoretical discussions of listening effort (e.g., Kuchinsky et al., 2014; Pichora-Fuller et al., 2016; Picou & Ricketts, 2014; Strauss & Francis, 2017). It reflects the existence of distinct (though mutually reinforcing) bodies of research on listening effort in cases of acoustic-phonetic interference, for example, noise, reverberation, competing speech (Koelewijn et al., 2012; Pichora-Fuller et al., 2016; Picou et al., 2016; Shinn-Cunningham & Best, 2008; Zekveld et al., 2011), and linguistic/cognitive interference or demand (Carroll & Ruigendijk, 2013; Garcia Lecumberri & Cooke, 2006; Garcia Lecumberri, Cooke, & Cutler, 2010; Hoen et al., 2007; Lewis, Vasishth, & Van Dyke, 2006; Mattys & Wiget, 2011; Van Engen & Peelle, 2014; Wingfield, McCoy, Peelle, Tun, & Cox, 2006); see Mattys et al. (2012) for an overview. However, although this binary distinction derives easily from patterns in research, and can be shown to be quite compatible with broader neuroscientific theories of attention (see discussion by Strauss & Francis, 2017), until recently there has been little evidence from the experimental literature to support or refute it, and the distinction is not universally accepted.

Furthermore, irrespective of whether the distinction between externally and internally directed attention is borne out by future research on the nature of exerted effort, such distinctions are still relevant to research on alleviating listening effort, as individuals may differ in terms of their ability to allocate capacity to different levels of processing, and different therapeutic strategies may be directed toward reducing different kinds of demands (Edwards, 2016; Strauss & Francis, 2017). For example, directional hearing aids may facilitate the direction of attention toward one auditory stream rather than another (Bernarding, Strauss, Hannemann, Seidler, & Corona-Strauss, 2017; Tremblay & Miller, 2014), reducing effort at the external or perceptual level, while the slowed rate and increased pausing in speech directed toward older listeners (Kemper, 1994; Kemper & Harden, 1999) and to and by nonnative speakers (Biersack, Kempe, & Knapton, 2005; Ginther, Dimova, & Yang, 2010) may facilitate lexical access or other aspects of comprehension in running speech (Winn, 2016; Winn & Moore, 2018), reducing effort at the internally directed or cognitive level (note that slowing speech rate may also affect the patterning of acoustic cues, thereby arguably also potentially affecting the distribution of externally directed attention). Indeed, the relative difficulty of identifying contexts or conditions that affect only internally or only externally directed attention may beg the

**FIGURE 2** Three models of speech perception illustrating the use of structural elements associated with listening effort. (a) Active processing incorporating aspects of both top-down and bottom-up components based on Heald and Nusbaum (2014) in this model, a mental representation of the signal (i) is compared to a linguistic pattern representation (n) generated on the basis of expectations and prior knowledge. The comparison generates feedback to modify either/both the structure of the perceptual representation and the linguistic interpretation. For example, the contribution or weighting of particular acoustic features in the perceptual representation may be emphasized or de-emphasized depending on their relative diagnosticity in a given context, while the hypothesized linguistic interpretation of the signal may be adjusted in response to changing awareness of the validity of expectations and prior knowledge. Demand on processing resources is incurred through the complexity of the comparison process and the possible need for multiple iterations of either or both feedback cycles when the initial perceptual representation is insufficiently determinative. Note, however, that this model makes no claims in itself as to the nature of the resources committed to either or both feedback loops, and it is entirely possible that both depend on the same capacity or capacities. (b) The original ELU model (J. Rönnberg et al., 2013). In this model, the incoming signal (which is explicitly multimodal) is initially converted into a phonological representation through automatic (i.e., not capacity-demanding) processes in the rapid, automatic, and multimodally bound PHOnological (RAMBPHO) episodic buffer. If this representation is sufficiently well-specified to match a linguistic representation (assumed to be syllabic in this case), then speech perception has occurred without the commitment of cognitive resources, that is, effortlessly. If, however, the phonological representation does not adequately match a single mental representation, then explicitly resource-demanding mechanisms are engaged. These mechanisms include both those we might consider to be more signal-oriented (such as shifting attentional focus and inhibition of irrelevant information), as well as those typically considered to involve higher levels of processing (such as inference and semantic integration), but the focus is primarily on the latter (J. Rönnberg et al., 2013). (c) The modified ELU model (based on an older representation) incorporating explicit top-down control of early sensory processing (Edwards, 2016). Here, the model described in (b) is augmented with a second, explicit locus toward which effort may be applied, namely a perceptual level of "feature extraction, object formation, and selective attention." Thus, in principle, the application of cognitive processing resources could alter the mental representation of the signal (in RAMBPHO) and, like the model shown in (a), there are two potentially distinct kinds of processes, one perceptual/signal-oriented and one more cognitive/semantic. ELU, Ease of Language Understanding question of whether different cognitive resources may be allocated at these different stages, let alone whether such differences in allocation are measurable. If both externally and internally directed attention (i.e., directed toward perceptual vs. cognitive processing) draw on the same pool of cognitive resources as suggested, for example, by Kiyonaga and Egner (2013) and Nobre et al. (2004), then the distinction between the two, while potentially significant for research on individual differences and reducing capacity demand, may be irrelevant or at least trivial with respect to quantifying expended effort (see discussion by Strauss & Francis, 2017).

On the other hand, research in other fields of cognitive psychology suggests that allocation of resources at different levels of information processing may be theoretically identifiable in terms of consequences for performance in the presence of distraction (e.g., Lavie, 2005, 2010; Park, Kim, & Chun, 2007). It is also possible that research to identify demand on cognitive resources (exerted effort) at different levels of information processing may demonstrate the existence of different patterns of response to different kinds of demand, perhaps across individuals, conditions, or measures. Future research aimed at identifying the contribution to listening effort of the allocation of different cognitive resources and/or at different levels of information processing will have to build on existing and future general theories of cognitive resources and the methods developed to investigate them.

## 3 | MEASURING LISTENING EFFORT

Thus far we have identified two key properties of current conceptualizations of listening effort: (a) listening effort is generally considered to be associated with the application of limited cognitive resources (i.e., attention) and (b) these resources may be applied at either or both an externally directed (perceptual) and an internally directed (cognitive) level of information processing. It remains to be seen, however, whether differences between these levels of application may be observed experimentally using existing behavioral or physiological measures associated with listening effort. Recent studies have begun to show that different measurements of "listening effort" collected while performing a single task do not necessarily correlate well with one another (Alhanbali, Dawes, Millman, & Munro, 2019; Lau, Hicks, Kroll, & Zupancic, 2019; Strand, Brown, Merchant, Brown, & Smith, 2018). It is possible that these different measures reflect different aspects or domains of cognitive demand or exertion (Lau et al., 2019). For example, there may be a difference in physiological response patterns between the deployment of attentional resources in the service of auditory scene analysis (i.e., externally directed attention) as compared with the engagement of long-term memory for lexical access (i.e., internally directed attention) (see Strauss & Francis, 2017). It is also possible that different patterns of response measured across multiple systems might still permit unique classification of different components or aspects of listening effort, if characterized appropriately, as suggested by Francis and Oliver (2018) (see also Khalaf et al., 2017; Strand et al., 2019). In either case, care must be taken when attempting to compare the implications of results across studies using different measures (Strand et al., 2018), and therefore it may be informative to consider the theoretical basis for assuming that any behavioral or physiological responses might be associated with cognitive effort.

We begin with the idea that exerting effort requires some degree of motivation (Richter, Gendolla, & Wright, 2016). Following the work of Barrett and colleagues, we take the perspective that motivation reflects the output of predictive mechanisms for regulating the expenditure of limited resources in order to maintain homeostasis (Barrett & Simmons, 2015; Kleckner et al., 2017; Touroutoglu et al., 2019). *Homeostasis* is a condition of physiological equilibrium of an organism relative to the environment (though it may be a dynamic equilibrium) (Berntson, Quigley, Norman, & Lozano, 2017), and is conceptually related to *core affect*, the neurophysiological state that varies moment-by moment, reflecting ongoing assessment of homeostasis (Barrett, 2006; Duncan & Barrett, 2007). When a change in the external or internal environment (e.g., a threatening sound or the expenditure of a limited resource) perturbs homeostasis, changes in core affect prompt adjustments to motivation in order to counteract or mitigate the predicted effect of the environmental change (Touroutoglu et al., 2019). Core affect is characterized according to the basic affective dimensions of valence and arousal (Barrett, 2006; Kleckner et al., 2017), with valence reflecting the degree of activation of positive (appetitive) versus negative (defensive) systems, and arousal related to the magnitude or intensity of motivation for action (see also the work of Bradley, Lang and colleagues, e.g., Lang et al., 1997).

Thus, for example, both a sudden and unexpected noise and also the prolonged need to commit limited cognitive resources such as working memory capacity to a difficult conversation may each change core affect. Both may alter valence (activating systems for defensive response to a perceived threat, or appetitive response to a perceived benefit to survival), and both may increase arousal (motivation for action). If they are strong enough, such changes in core affect will (in combination with other signals) change the listener's motivation to act. Even when this motivational change is not sufficient to prompt immediate behavioral changes (i.e., flight), differences in physiological and emotional correlates of core affect across tasks and/or listeners can provide insight into the causes and consequences of listening effort.

Core affect may be measured in terms of the activity of many different physiological systems. Such affectively relevant systems include the autonomic nervous system (ANS, Bradley & Lang, 2000) and the somatic nervous system, especially with respect to facial expressions (Cacioppo et al., 2000), as well as basic cognitive systems such as selective attention and memory (Duncan & Barrett, 2007; Touroutoglu et al., 2012). Indeed, as we will discuss below, the interaction between affective and attentional/cognitive processes is fundamental to our understanding of listening effort. More specifically relevant for our discussion here, in addition to reflecting the current status of the organism, core affect provides a basis for the cognitive interpretation of internal states that we identify as emotions (Barrett & Bliss-Moreau, 2009; Russell & Barrett, 1999), making it indirectly accessible to description via introspection and self-report as well as objective physiological assessment.

In this section, we describe currently common methods for quantifying listening effort, focusing on the interplay between assessing exerted and assessed effort. We distinguish first between behavioral assessments and physiological ones and, within physiological assessments, between those that quantify responses related to activity in the peripheral (especially autonomic) nervous system and those related to central nervous system function. We follow this with a brief discussion of how these same measures have been related to affective responses in preparation for a final discussion of the relationship between listening effort, affective response, and attentional control.

## 3.1 | Behavioral measures

Behavioral methods for quantifying listening effort include subjective (self-report) instruments, measures of subsequent memory of items heard in effortful contexts, and measurements of task performance or response time, often in the context of dual-task paradigms. These methods are intended either to: (a) quantify the listeners' explicit awareness of the experience of expending effort as required by a task (self-report) or (b) to derive a covert measure of the relative amount of cognitive resources devoted to a particular listening task (especially attention and/or working memory capacity).

### 3.1.1 | Self-report

Subjective assessments of listening effort typically consist of surveys in which listeners are asked directly how much effort was required to perform the task. Such assessments typically consist of verbal questionnaires in which listeners explicitly rate how much effort is required to understand or recognize the speech in question (Larsby, Hällgren, Lyxell, & Arlinger, 2005; Zekveld, Kramer, & Festen, 2010). Other surveys consist of general task load assessments such as the NASA Task Load Index (Hart & Staveland, 1988) that may be slightly modified for use in listening contexts (Francis et al., 2016; Mackersie & Cones, 2011). The simplest surveys of listening effort may consist of a single question (Picou, Ricketts, & Hornsby, 2011), while others, for example, the Speech, Spatial and Qualities of Hearing Scale (SSQ, Gatehouse & Noble, 2004) are very long and detailed, reflecting the somewhat uncertain but likely multidimensional nature of listening demands (Akeroyd, Guy, Harrison, & Suller, 2014). Still others such as the SSQ-12 (Noble, Jensen, Naylor, Bhullar, & Akeroyd, 2013) attempt to strike a balance between comprehensiveness and usability in time-sensitive contexts such as the audiology clinic.

Asking listeners to consciously evaluate the effort required to perform a particular listening task is conceptually similar to the kind of conscious, introspective evaluations that are thought to underlie communicative decisions based on long-term experience (such as whether to abandon a hearing aid) because such evaluations integrate the memory of the effort itself with the listener's feelings about expending that effort (cf. Francis & Oliver, 2018). On the other hand, people are generally not able to report accurately on perceptual or memory processes, and may only be accurate about other mental processes when they are particularly salient and consistent with a priori expectations (see discussion by Nisbett & Wilson, 1977). Indeed, recent evidence suggests that listeners asked to rate the effort required to perform a task may be answering an easier question ("how did I perform") (Moore & Picou, 2018) and it is possible that an even more general question is being answered, for example, "how do I feel" (Craig, 2009). Thus, self-report measures directly reflect listeners' conscious awareness of their effort and/or their expectations about their effort, which can be highly relevant to clinical applications of the study of listening effort and may even be more sensitive than other methods when applied in audiological contexts (Johnson et al., 2015). However, by directing listeners' conscious attention to their own internal states, self-report measures necessarily reflect how effortful listeners *feel* the task or context to be. Thus, they may serve most effectively as measures of assessed effort rather than of exerted effort.

### 3.1.2 | Memory measures

The close connection between theories of listening effort and theories of the role of working memory in speech perception (as discussed above; see also Besser et al., 2013) suggests that performance on memory-demanding speech tasks may serve as a reliable indicator of listening effort (cf. discussion by Rudner, 2016). Indeed, many of the studies that first demonstrated the capacity-demanding nature of speech perception used measures of memory performance (McCoy et al., 2005; Pichora-Fuller et al., 1995; Rabbitt, 1968, 1991; Surprenant, 1999, 2007). For example, Surprenant (1999) assessed immediate recognition and subsequent serial recall of lists of nonsense syllables presented in noise at different signal-to-noise ratios (SNR). She found that, even when performance on syllable recognition was comparable across SNRs, recall was significantly impaired as SNR decreased (noise level increased) and this decrease was similar across all serial positions in the list.

Recent work by Mishra, Lunner, Stenfelt, Rönnberg, and Rudner (2013a, 2013b); Mishra, Stenfelt, Lunner, Rönnberg, and Rudner (2014) formalizes this observation in a set of cognitive spare capacity tests (CSCTs). These tests are designed to measure participants' memory for speech stimuli (two-digit numbers) under various noise and amplification conditions tailored to equate individual listeners' recognition performance. The idea is that, when speech perception is challenging, listeners will vary in terms of the amount of working memory capacity they must devote to enable recognition at a given performance level. Those with greater overall capacity will therefore have more spare capacity available to devote to remembering speech and manipulating the remembered items once the speech has been recognized. Results of CSCT tests have been used to argue that older adults with hearing loss have less spare capacity than younger adults with normal hearing, and that the two groups may also apply cognitive processing in different ways, perhaps especially with respect to the role of long term memory (Mishra et al., 2014). Other tests including the Sentence-Final Word Identification and Recall (Ng, Rudner, Lunner, Pedersen, & Rönnberg, 2013; Ng, Rudner, Lunner, & Rönnberg, 2015) and the Auditory Inference Span Test (N. Rönnberg et al., 2014) use sentences rather than numbers as stimuli (see Rudner, 2016 for a thorough discussion of similarities and differences between these tests). Of particular note here is that most of the tasks that employ measures of memory as explicit quantification of listening effort consist of *content embedded* (span) tasks in which the items to be remembered are relevant to the primary tasks (see discussion by Was, Rawson, Bailey, & Dunlosky, 2011). With respect to identifying these measures with different theoretical aspects of listening effort, it seems likely that such memory-based measures are most plausibly associated with exerted effort related to the engagement of later-occurring mechanisms, that is, those that we have referred to as internally directed attention, especially those that interact with long-term memory processes such as lexical access and the more general coping mechanisms described by Shinn-Cunningham (2008).

### 3.1.3 | Response time and dual-task measures

A third common experimental method for assessing task load that may also be applied to listening effort involves measuring a listener's accuracy and response time to a simple task, for example, a speeded target-monitoring task in which listeners hear a stream of words and are instructed to respond every time they hear the word “ball” (Magnuson & Nusbaum, 2007). The assumption is that, all else being equal, more effortful processes consume more processing resources than do less effortful ones. As the proportion of available resources applied to a particular task reaches maximum, processing time should slow down. Therefore, since processing resources are limited, more effortful tasks take longer to complete than do less effortful ones and, conversely, a manipulation of task parameters that results in slower response times is assumed to have increased the effort demanded by the task.

In *dual-task methods*, two tasks are conducted simultaneously. The expectation is that both tasks will draw on the same limited pool of cognitive resources (Norman & Bobrow, 1975). There are two applications of dual-task paradigms, depending on which task is varied in terms of demand. In a probe task configuration, the task designated as primary is manipulated in terms of demanded effort (i.e., lower- and higher-effort conditions are presented), while the secondary task is kept at a constant level of demand. As the primary task demands more effort, it will consume a larger proportion of available resources, meaning that the secondary task will exhibit the consequences of reduced resource availability: slower completion time and more or more serious errors (Fraser, Gagné, Alepins, & Dubois, 2010; Gagne, Besser, & Lemke, 2017; Sarampalis et al., 2009). Thus, performance on the secondary task may be used as an index of resources committed to the primary task under different conditions. Alternatively, manipulating demand in the secondary task may be used to manipulate the availability of resources for the primary task. In this case, the primary task is held constant but demand on the secondary task is varied across conditions (i.e., in a low vs. high digit preload task, cf. Francis, 2010). Higher-demand secondary tasks “soak up” a greater proportion of the total available resources than do lower-demand ones, so that the resources remaining available for the primary task will vary as a function of secondary task demand, allowing one to investigate the effects of resource availability on primary task performance.

Because response time and dual-task measures are argued to reflect operational properties of the mechanisms engaged in listening, they can be most easily considered measures of exerted effort. However, it must be noted that the application of these measures depends on a very specific model of resource consumption-based task interference, therefore their results may be open to competing interpretations (cf. Navon, 1984; Pashler & Johnston, 1989). In particular, even when one adopts a resource model of attentional capacity, care must be taken to employ tasks for which there is a reasonable expectation that they both draw equally on the same pool of resources (Navon & Gopher, 1979) and that any changes observed in "consumption" of resources do not derive from changes in the way participants approach or structure the overall dual-task activity (Cheng, 1985). For this reason, it is usually not sufficient to compare data from single- versus dual-task conditions (see discussion by Gallun, Mason, & Kidd, 2007), but rather it is necessary to compare results between two dual-task conditions with different levels of demand in (only) one of the two tasks. The interested reader is referred to the discussion by Ahissar, Laiwand, and Hochstein (2001) and Handy (2000). Nevertheless, dual-task methods have proven quite successful in identifying a role for effort in listening behavior, for example, related to hearing aid setting preferences (see Gagne et al., 2017 for review).

### 3.2 | Physiological measures

The characterization of effort in terms of the allocation of limited resources might suggest that we should be able to measure those resources before and after mental exertion and thus calculate exactly how much effort a given task has required. Although attempts to link cognitive effort to consumption of measurable metabolic resources have been inconclusive (Kramer, Teunissen, & Zekveld, 2016; Kurzban, 2010; Orquin & Kurzban, 2016), it is possible that such resources are more properly associated with related constructs such as motivation (Molden et al., 2012), and/or that other metabolites are more directly related to effort (Westbrook & Braver, 2016). For now, though, we relate physiological measures to the exertion of cognitive effort in terms of the operation of abstract (though necessarily neurally instantiated) cognitive mechanisms including attention (Strauss & Francis, 2017) and/or working memory (Pichora-Fuller et al., 2016; Rudner, 2016; Wingfield, 2016). Because these mechanisms must be operating within the brain, we should still be able to measure exerted effort by measuring appropriate correlates of brain function and neural response during task performance. Thus, physiological correlates of listening effort may be sought in the same brain regions and via the same physiological responses that correspond to the engagement of selective attention and/or the deployment of working memory capacity.

Historically, measurement of physiological consequences of cognitive activities has concentrated on two conceptually distinct neural systems: the autonomic and the central nervous system. In addition to these measures, we also consider blood- or saliva-borne chemicals associated with neural activity as a third potential method for identifying physiological responses to effort. While there has yet been relatively little research on neurochemical correlates of listening effort, such measures bear on our subsequent discussion of the role of affective response to effortful listening in long-term health.

#### 3.2.1 | Peripheral measures

The ANS governs the function of organs related to survival, including the respiratory and cardiovascular systems, various hormonal and neurotransmitter systems, and those governing temperature regulation, digestion and elimination (see Wehrwein, Orer, & Barman, 2016). The ANS maintains homeostasis by constantly adjusting the behavior of physiological systems in a constantly shifting balance between states of action and rest (Berntson & Cacioppo, 2007) in a process sometimes called "allostasis" (McEwen, 1998; see Day, 2005 for discussion of terminology). Two major branches of the ANS are the sympathetic and parasympathetic nervous systems (here, SNS and PNS). The SNS is often associated with physical response to immediate threat ("fight or flight") while the PNS is often considered as bringing the body back down from SNS-instigated arousal ("rest and digest"). SNS arousal is associated with increased heart rate (HR) and blood pressure, pupil dilation, sweating, the narrowing of peripheral arteries (and concomitant skin cooling), and the release of catecholamines (epinephrine, norepinephrine) into the bloodstream. In contrast, PNS arousal results in a slowing HR, lowered blood pressure, relaxation of peripheral vasoconstriction, and pupil contraction. However, as discussed briefly by Francis and Oliver (2018), the actual relationship between these systems is far more complex than simple complementarity. Interested readers are referred to work by Berntson and Cacioppo (2007) and D. S. Goldstein (2013) for more comprehensive reviews. The autonomic and central nervous systems also have a complex relationship of reciprocal influence, and the behavior of autonomically controlled end organs has been used to evaluate cognitive effort since at least the 1960s (e.g., Kahneman, 1973; Kahneman & Beatty, 1966).

Interested readers are referred to reviews by Critchley (2002), Wright and Kirby (2001), and Zekveld, Koelewijn, and Kramer (2018).

### *Electrodermal response*

Electrodermal activity (EDA) refers to changes in electrical conductance through the skin, especially of the palm of the hand or sole of the feet, as a result of sympathetically governed eccrine sweat gland activity (Andreassi, 2007; Boucsein, 1992; Dawson, Schell, & Filion, 2007). Measures of skin conductance can be characterized 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, that is, in the absence of an identifiable stimulating event (Dawson et al., 2007).

SCL increases with increased demand on working memory, for example, in an N-Back task (Mehler, Reimer, & Coughlin, 2012), and decreases with declines in vigilance (Davies & Krkovic, 1965). SCR amplitude is sensitive to stimulus intensity, and also declines with repeated exposure (habituation) (Dawson et al., 2007). Electrodermal measures have been proposed as markers of selective attention, especially with respect to emotionally salient stimuli (Bradley, 2009; Cohen, 2014) and as a component of the *orienting response* (Barry, MacDonald, De Blasio, & Steiner, 2013; Cohen, 2014). With respect to listening effort, some studies (Francis et al., 2016; Mackersie & Calderon-Moultrie, 2016; Mackersie & Cones, 2011; S. Seeman & Sims, 2015) suggest that different aspects of EDA may be useful for examining factors related to selective attention in speech perception, though Cvijanović, Kechichian, Janse, and Kohlrausch (2017) and Mackersie, MacPhee, and Heldt (2015) also reported null results for some of the same EDA-based measures. Across these studies, the overall pattern of results suggests that electrodermal responses can be reliable indicators of exerted cognitive effort as they are sensitive to the attentional demands of a task (see Francis & Oliver, 2018 for discussion), and that SCRs in particular may represent that the organism has recognized a stimulus as requiring the commitment of attentional resources (Öhman, 1979) or as being otherwise relevant for further cognitive processing (Bradley, 2009).

### *HR and heart rate variability*

HR is the frequency of the heartbeat, often measured in beats per minute. It may also be measured in the time domain in terms of the period of the ECG signal. Changes in HR are typically modulated by both sympathetic and parasympathetic activity (Berntson & Cacioppo, 2007).

A few studies of listening effort using HR as a dependent measure have shown a small decrease in HR within a few seconds after stimulus presentation (Francis et al., 2016), while others have found an overall task difficulty-related increase in HR over longer (2 min) spans containing multiple trials (S. Seeman & Sims, 2015), and still others report no change in HR with increased listening task demands (Cvijanović et al., 2017; Mackersie & Cones, 2011). A major disadvantage to the use of HR alone as a measure of effort is that, as mentioned above, it is governed by both sympathetic and parasympathetic innervation, which complicates interpretation (Richter et al., 2016). When such differentiation is desirable, researchers tend to incorporate derived measures such as heart rate variability (HRV) or pre-ejection period (PEP) (see below).

HRV can be measured in terms of temporal variability in period duration over time (e.g., the standard deviation of the normal-to-normal interval (Berntson et al., 2017) or the square root of the mean squared difference between successive heart periods (Mackersie & Calderon-Moultrie, 2016). It is now also common to employ frequency-based analyses of the ECG signal (Berntson et al., 2017; Shaffer, McCraty, & Zerr, 2014). Results from studies investigating HRV while listening to speech in adverse conditions are mixed, and may be complicated by the fact that individual differences in resting HRV seem to predict performance on cognitively demanding tasks involving sustained attention, executive function, working memory, and response inhibition (Thayer, Hansen, Saus-Rose, & Johnsen, 2009). In other words, HRV may be more of a trait that predicts performance on capacity-demanding tasks rather than a reliable correlate of changes in resource allocation (exerted effort). Nevertheless, some studies have found an increase in HRV associated with increased listening task demand, at least in some populations (Mackersie et al., 2015; S. Seeman & Sims, 2015).

### *Pre-ejection period*

PEP is a measure derived from a combination of ECG and echo-cardiogram recordings, reflecting the amount of time that elapses between the beginning of ventricular depolarization and the opening of the aortic valve, a span also referred to as the electrical systole (Berntson & Cacioppo, 2007). PEP is governed purely sympathetically, and has been related to measures of motivation and effort (Gendolla, Wright, & Richter, 2012), including recent work on listening effort (Richter, 2016). In particular, PEP appears to reflect exertion of mental effort, perhaps especially the engagement of working memory capacity, such that it increases with increasing working memory task demand until a point at which the task is too difficult and participants give up (Richter, Friedrich, & Gendolla, 2008). Moreover, PEP is affected by motivation (i.e., the importance of success to participants) (Richter, 2016; Richter, Baeriswyl, & Roets, 2012), supporting its characterization as a measure of either exerted effort or perhaps intention to exert effort.

#### *Peripheral vasoconstriction*

Blood volume pulse amplitude is a measure of the volume of blood flow in the peripheral capillaries at systole. It has 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, Moleman, Van-Steenis, & Boomsma, 1989) and mental arithmetic (H. S. Goldstein & Edelberg, 1997), and such decrease has been linked specifically to the increased investment of mental effort in a task, such that pulse amplitude decreases parametrically with increase in working memory load (Iani, Gopher, & Lavie, 2004). As yet, only one study (Francis et al., 2016) suggests that blood volume pulse amplitude (BVPA) may be associated with listening effort, having identified a decrease in BVPA that peaks a few seconds after stimulus presentation. However, a decrease in BVPA is also associated with an increase in negative emotional response (Kreibig, 2010), so it is possible that this reflects more of an evaluative reaction to the effort rather than the effort itself (see Francis & Oliver, 2018 for discussion).

#### *Blood pressure*

Systolic blood pressure (SBP) has also been associated with cognitive demand (Richter et al., 2008; Wright & Dill, 1993). Although SBP has, to our knowledge, not yet been investigated in the context of listening effort, it may turn out to be a significant measure in the future because SBP reactivity is controlled primarily through beta-adrenergic pathways and thus, like PEP, represents a more purely sympathetic measure of cardiovascular reactivity compared to, for example, HR (which is both sympathetically and parasympathetically governed). More importantly, however, SBP reactivity may be affected by overall fatigue (Wright et al., 2007), suggesting that in addition to representing a potential measure of exerted effort similar to that provided by PEP (see discussion by Richter, 2016), measurement of SBP as a correlate of listening effort may also provide a physiological link between sympathetically arousing listening effort, ensuing fatigue (Hornsby et al., 2016), and long-term health problems associated with chronically elevated blood pressure (Gates, Cobb, D'Agostino, & Wolf, 1993).

#### *Pupil dilation*

Pupil dilation refers to change in the diameter of the pupil of the eye under conditions unrelated to illumination, typically either emotional or cognitive in nature. The pupil dilation response has long been associated with tasks requiring the application of cognitive effort (Beatty, 1982; Kahneman, 1973; Kahneman & Beatty, 1966), including listening effort (Koelewijn, Shinn-Cunningham, Zekveld, & Kramer, 2014; Kramer, Kapteyn, Festen, & Kuik, 1997; Kuchinsky et al., 2013; Winn, 2016; Winn et al., 2015; Zekveld et al., 2011, 2018; Zekveld, Rudner, Kramer, Lyzenga, & Rönnberg, 2014). In terms of specific cognitive mechanisms, pupil dilation has been associated with the engagement of selective attention (Wierda, van Rijn, Taatgen, & Martens, 2012) and working memory (Goldinger & 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, Nieuwenhuis, Jepma, & Cohen, 2010; Kahneman, Peavler, & Onuska, 1968).

Pupil dilation is governed both sympathetically and parasympathetically (Steinhauer, Siegle, Condray, & Pless, 2004), with parasympathetic arousal causing constriction and sympathetic arousal causing dilation. Although this means that a dilatory response may result from either arousal of the SNS or inhibition of the PNS (Bradley, Sapigao, & Lang, 2017), due to the slightly different time scales on which these two systems may operate, these contributions may be dissociable in the pupillary response signal through statistical means (Wetzel, Buttelmann, Schieler, & Widmann, 2016; Widmann, Schröger, & Wetzel, 2017). Although the following hypothesis is still highly speculative at the moment, we suggest that this may be significant because, although both cognitive and affective (emotional) stimulation may result in pupil dilation, emotionally evocative stimuli appear to cause pupil dilation primarily through sympathetic arousal (Bradley et al., 2017), while cognitive demand induces primarily parasympathetic withdrawal (Steinhauer et al., 2004). Thus, pupil dilation may be the preferred single measure for assessing cognitive demand during effortful listening, but it may be necessary to develop methods for distinguishing between cognitive and affective contributors to the response (see discussion by Francis & Oliver, 2018).

### 3.2.2 | Autonomic responses and affect

The literature on emotional or affective interpretations of psychophysiological, especially autonomic, responses is vast, and we can only briefly summarize it here. Interested readers are referred to general overviews of psychophysiology such as those by Andreassi (2007) and Potter and Bolls (2012), and also to chapters in handbooks of psychophysiology including Bradley and Lang (2000) and Mauss and Robinson (2010), and review articles such as those by Crowley et al. (2016), Kreibig (2010), and Larson et al. (2008). In short, all of the autonomic measurements we have discussed are associated with a wide variety of emotional responses (Kreibig, 2010), but there is little strong consensus as to whether or how specific autonomic responses relate to specific emotional categories. For example, Quigley and Barrett (2014) discuss the results of studies that were intended to identify patterns of ANS activity with specific emotions (Christie & Friedman, 2004; Kragel & LaBar, 2016; Stephens et al., 2010), but that failed to show any large-scale agreement. Nevertheless, some broad generalizations may be made about the relevance of the autonomically governed systems we have discussed with respect to arousal and valence dimensions of core affect (Barrett, 2006; Russell & Barrett, 1999). In particular, EDA is primarily associated with the affective dimension of arousal (Bradley, 2009; Lang, 1995) as is the sympathetic component of pupil dilation (Bradley, Miccoli, Escrig, & Lang, 2008; Bradley et al., 2017), while changes in cardiac activity such as HR may be more strongly associated with valence (Lang, 1995; Lang et al., 1997; Neumann & Waldstein, 2001). Francis and Oliver (2018), observing the wide variety of physiological response patterns associated with listening effort across studies (as demonstrated explicitly by Alhanbali et al., 2019), proposed that multi-system patterns of physiological response might be able to function as markers (in the sense of Richter & Slade, 2017) of listening effort-related affective states in much the same way that the orienting response is defined in terms of multiple autonomic signals, but is taken to measure a single psychological construct (i.e., engagement of selective attention) (Barry et al., 2013). Further research will be necessary to determine whether this approach to physiological assessment of listening effort may be successful.

### 3.2.3 | Central nervous system measures

Alternatively, one might propose that the best way to distinguish the application of specific cognitive resources or the affective response to their task-related depletion might be to record activity in the brain itself. Here, we discuss two established methods for assessing listening effort using functional magnetic resonance imaging (fMRI) and electroencephalography (EEG), and note that the functional anatomical networks identified in this research appear to overlap considerably with those identified in affective processes as well.

*Functional magnetic resonance imaging*

Studies using functional brain imaging have shown increased activity in brain regions associated with attention and working memory when listening to speech that is more difficult to understand because it is degraded (noise-vocoded) (Wild et al., 2012) or masked by noise (Zekveld et al., 2011). The assumption in such studies is that observed regional changes in blood oxygen level reflect changes in demand on brain networks recruited for task-related cognitive processing. A meta-analysis of recent studies of comparing speech perception in easier versus harder conditions suggests that a cingulo-opercular network including bilateral regions in dorsal cingulate, inferior frontal and anterior insular cortex and the interrelated white matter tracts, is crucially activated when listeners are intending to perform a listening task that is challenging but that they are still capable of performing accurately (Eckert et al., 2016). Eckert and colleagues argue that this network instantiates a kind of attentional control network responsible for modulating behavior (including autonomic arousal, memory retrieval, and response selection and inhibition) based on evaluations of performance, task difficulty, and motivation (Eckert et al., 2016).

Peelle (2018) summarizes work relating brain activity to speech intelligibility and identifies a variety of brain networks active during effortful listening to different kinds of degraded speech. These networks include the cingulo-opercular network discussed by Eckert and colleagues as well as core speech networks that incorporate regions including left medial and superior temporal and inferior frontal gyrus and also networks identified with more general cognitive functions such as regions in premotor cortex implicated in verbal working memory. Note that the functional role of all of these networks is complex, and all are implicated in multiple cognitive functions, so their inclusion here should not be taken as suggesting that they are involved only in these particular functions. For example, the cingulo-opercular network, here described specifically as governing performance monitoring, is implicated in whole or in part in a wide variety of attention-related activity, including monitoring of performance in a speech task (Vaden, Teubner-Rhodes, Ahlstrom, Dubno, & Eckert, 2017), maintenance and updating of attention (Han et al., 2018), general alertness (Sadaghiani & D'Esposito, 2015), and (with respect to the role of the insula especially) emotional/interoceptive self-monitoring (Craig, 2009). Thus, while the primary application of fMRI has long been seen as functional localization (Posner, Petersen, Fox, & Raichle, 1988), research has recently shifted toward investigation of large-scale, multifunctional networks (Bressler & Menon, 2010) and such an approach seems more compatible with the multifaceted nature of listening effort as well.

### *Electroencephalography*

Another way of characterizing brain activity, especially whole-brain activity, is by recording electrical activity at the scalp, a technique known as electroencephalography. Because brain activity is inherently electrochemical, brain behavior can be measured in terms of patterns of electrical signals given off during specific tasks, or no task at all. There exists a vast literature on the use of EEG in psychophysiology (Pizzagalli, 2007), so we will focus here only on two of the measures that have been explicitly linked to listening effort.

Electrical activity recorded at the scalp typically exhibits some degree of voltage oscillation reflecting the summed postsynaptic potentials of masses of neurons in the brain, especially those arranged in coherent structures ("cortical microcolumns") (Pizzagalli, 2007). These oscillations range in frequency from about 1 to 50 Hz, and have a magnitude of voltage change ranging from about 10 to 50 μV, with higher amplitudes reflecting greater synchronicity of neuronal firing. These frequencies are generally grouped into bands; here we are primarily concerned with alpha (8–13 Hz) and theta (4–8 Hz) frequencies.

Alpha oscillations are observed during a relaxed but awake state, especially with closed eyes. At rest they are typically strongest above posterior (occipital, temporal, and parietal) brain regions. Desynchronization (reduction in amplitude) or elimination of alpha oscillations is particularly noticeable when subjects are suddenly alerted or otherwise caused to increase their mental activity. Alpha oscillations are not just a "default" or resting-state rhythm, however, as alpha synchrony has, for example, been observed to increase over cortical regions associated with task-irrelevant stimuli (Haegens, Luther, & Jensen, 2012). Thus, alpha *desynchronization* (decreased alpha power) has been cited as a marker of cognitive or neural engagement especially of long term memory (Klimesch, 1999), while alpha *synchronization* (increased alpha power) may be associated with inhibition of distracting information, especially when observed over cortical regions typically involved in processing that type of information (Weisz, Hartmann, Müller, & Obleser, 2011).

With respect to speech perception, it appears that alpha desynchronization is associated with listening to degraded (noise-vocoded) speech (Obleser & Weisz, 2011), but increased alpha power (synchronization) has also been observed to be correlated with pupil dilation when listening to speech in noise (McMahon et al., 2016). A plausible interpretation of this finding is that desynchronization corresponds to increased attention directed toward processing the target signal, while synchronization reflects engagement of inhibitory mechanisms to suppress processing of the noise signal (Dimitrijevic, Smith, Kadis, & Moore, 2017; Strauβ, Wöstmann, & Obleser, 2014). However, given that both of these mechanisms could plausibly be identified as reflecting exerted effort in the form of externally directed attentional resources, further research, perhaps especially involving methods for localizing source regions for these task-related changes in alpha power, will be necessary to disentangle the degree to which alpha synchronization and desynchronization reflect similar or different aspects of listening effort.

Like alpha, theta oscillations (4–8 Hz) are also associated with alertness and cognitive processing. We are primarily concerned with the oscillation that is most strongly observed in frontal regions, also known as *frontal midline theta* (FMθ), which is strongly associated with attention and mental effort (Pizzagalli, 2007), especially cognitive control (Cavanagh & Frank, 2014; Sauseng, Griesmayr, Freunberger, & Klimesch, 2010) and sustained attention (Clayton, Yeung, & Kadosh, 2015), but also anxiety (Cavanagh & Shackman, 2015). FMθ has also recently been shown to pattern with pupil dilation measures of effort in a manner similar to that of alpha desynchronization (Williams, Kappen, Hassall, Wright, & Krigolson, 2018). A second, more broadly distributed (non-site-specific) theta oscillation has also been associated with decreased alertness and poorer information processing (Pizzagalli, 2007; Schachter, 1977), but this may also simply reflect an increase in FMθ as result of the engagement of compensatory mechanisms (i.e., the previously identified control of working memory) under certain task conditions (Wascher et al., 2014).

With respect to listening effort more specifically, Wisniewski and colleagues (Wisniewski, 2017; Wisniewski, Iyer, Thompson, & Simpson, 2018; Wisniewski et al., 2015), using a variety of nonspeech auditory tasks, have demonstrated an increase in theta band power localized to frontal regions along with a simultaneous increase in posterior (likely occipital) alpha power when listening becomes more effortful. As previously discussed, this could be associated with increasing inhibition of irrelevant (in this case probably visual) information. Similarly, Marsella et al. (2017) also found an effort-related reduction in alpha power, though localized over parietal rather than occipital sites, in children with hearing impairment performing a variety of speech-in-noise tasks, possibly reflecting increased inhibition of competing (noise) stimuli. However, they did not find any changes in theta band power. Wisniewski and colleagues attribute the FMθ results to engagement of working memory, while the more posterior reduction in alpha band power is attributed to inhibition of task-irrelevant stimuli. However, as discussed above, it may also reflect a more general engagement of systems of cognitive control, including but not limited to increased demand on working memory.

Theta oscillations in anterior cortex may also provide information about the direction of selective attention to speech in terms of their ability to phase-lock to the amplitude envelope of an attended speech signal, which also tends to be modulated at about 4–8 Hz (Chi, Gao, Guyton, Ru, & Shamma, 1999) (cf. work by Bernarding et al., 2013, 2017; Peelle & Davis, 2012; Peelle, Gross, & Davis, 2012; Viswanathan, Bharadwaj, & Shinn-Cunningham, 2016). This hypothesis is based in part on the finding that the degree of phase synchrony between neural oscillations and the acoustic signal is related to the intelligibility of (and possibly the direction of attention to) the speech signal (Ghitza, 2011; Giraud & Poeppel, 2012; Peelle & Davis, 2012; Viswanathan et al., 2016), as well as the rated listening effort (Bernarding et al., 2017). However, further research will be needed to reconcile more general cognitive/affective interpretations of theta band power with this much more speech-specific interpretation of phase synchrony.

*Event related potential*

Finally, it is also possible to sum or average EEG signals that have been time-locked to a particular event, typically a stimulus onset or offset, to obtain an event related potential (ERP) signal. A thorough discussion of ERP signals is beyond the scope of this article (Fabiani, Gratton, & Federmeier, 2007), even if we constrain discussion to those that have been considered to relate to cognitive demand (Kok, 1997). In general, poorer listening conditions appear to result in increased amplitude, decreased latency and poorer phase synchrony for the N1 component (Bernarding et al., 2012; Obleser & Kotz, 2011), while Song and Iverson (2018) have recently argued that the magnitude of the N400 component may also reflect the degree of mental effort at the lexical level when listening to nonnative accented speech.

The approach used by Song and Iverson (2018) has promise as a method for identifying demand on different cognitive processes (i.e., externally vs. internally directed) because individual ERP components are frequently identified with different types of information processing in the brain. Thus, if magnitude and/or latency of ERP components is taken as a measure of effort, then it may be possible to determine how a particular condition engages specific effortful processes (i.e., attention, working memory, lexical access) by examining the magnitude and/or latency of different ERP components in that condition. On the other hand, the evocation of many ERP components is highly paradigm-specific, so this method for assessing relative effort exerted across different systems requires comparison across different behavioral paradigms. One promising potential solution to this problem can be found in recent work by Choi and colleagues (Choi, Rajaram, Varghese, & Shinn-Cunningham, 2013; Kim et al., 2018) in which single-trial EEG methods (Choi et al., 2013) are combined with source localization models to identify stimulus processing-related changes in the time-course and amplitude properties of ERP components associated with a single stimulus as they arise in different brain regions (Kim et al., 2018). Specifically, increasing masking noise levels resulted in a decrease in amplitude of earlier-occurring activity associated with posterior temporoparietal areas, and a concomitant increase in amplitude of later-occurring activity associated with more inferior, frontal areas. These results might suggest that as masking noise increases, the ability to accurately identify words based on acoustic-phonetic properties alone decreases (in posterior temporal regions) and the engagement of post-perceptual cognitive (i.e., top-down, “filling in”) mechanisms increases (in lateral frontal regions). Future research will certainly be necessary to definitively answer this question, but at this point, the neuroanatomical evidence seems to be accruing to support the idea that there may be at least two functionally and physiologically distinguishable sorts of mechanisms engaged in effortful listening: one associated more with auditory/acoustic processes, and one related more to coping with failures at that earlier level.

### 3.2.4 | Central affective networks

Affect, too, is associated with large and widely distributed neural networks that overlap to a considerable degree with the networks already identified with effort (Barrett & Bliss-Moreau, 2009; Duncan & Barrett, 2007; Johnson et al., 2015; Kleckner et al., 2017; Wagner et al., 2008; Xia et al., 2017). For example, the cingulo-opercular network, identified by Eckert et al. (2016) as being involved in monitoring and optimizing performance in difficult speech perception tasks, also appears to include a number of key regions integral to the allostatic/interoceptive networks described by Kleckner et al. (2017), including the salience network described by Touroutoglou et al. (2012). It is not possible here to definitively determine the degree and location of this overlap due to differences in terminology and imaging methods across studies. However, the involvement of portions of the cingulo-opercular network in both effortful listening and affective response is of particular interest because this system is proposed to be involved in the ongoing estimation of whether engaging in an effortful listening task continues to be worth the effort (i.e., is worth the contribution of resources) (Eckert et al., 2016). Furthermore, the cingulo-opercular network has also been identified in whole or in part with affectively related functions such as affective arousal (Satpute et al., 2019), self-awareness and monitoring of interoceptive information (Craig, 2009; Touroutoglou et al., 2019), and core affect more broadly defined (Duncan & Barrett, 2007).

Electrophysiological measures of brain activity may also simultaneously reflect affective as well as cognitive processing. For example, in addition to being associated with the engagement of attention and mental effort, FMθ is anatomically associated with activity in midcingulate cortex, a putative domain-general hub for applying information about threat and potential punishment to modulate systems for affective response, directing selective attention, and controlling goal-directed behavior (Shackman et al., 2011; Touroutoglou et al., 2019). Increases in the power of FMθ therefore may be interpreted as reflecting both the affective and cognitive (perhaps especially attentional, Clayton et al., 2015) aspects of adaptive control processes, encompassing both the affective response to recognition of error in a previous response and adjustment of the application of cognitive mechanisms for the future (Cavanagh & Shackman, 2015; Touroutoglou et al., 2019).

### 3.2.5 | Neurochemistry

There are two primary sources for measurable, cognitive effort-related changes in blood neurochemistry related to effort: (a) the hypothalamic–pituitary–adrenal axis (HPA) that produces the hormones cortisol and aldosterone (among others), and (b) the sympathetic–adrenal–medullary (SAM) axis that produces the catecholamines epinephrine and norepinephrine (among others). HPA activity is typically associated with psychological (especially psychosocial) stressors and feelings of lack of control (distress), while the kinds of short-term cognitive demands typically studied in research on listening effort seem more likely to engage the SAM system (Dickerson & Kemeny, 2004; Skoluda et al., 2015). There is some evidence that physiological markers of performance-related stress may only arise when high levels of effort are maintained, suggesting a possible trade-off between cognitive effort and occupational stress (Tafalla & Evans, 1997). With respect to listening effort, there is some epidemiological evidence that individuals with hearing loss and those who work in noise exhibit higher levels of salivary cortisol compared to those with normal hearing (Fisher et al., 2014) or those who work in quiet (Babisch, 2003; Bigert, Bluhm, & Theorell, 2005; though cf. Stokholm et al., 2014 for a rigorous failure to confirm such a link) respectively, suggesting that, at some stage, both systems may be engaged (either separately or together) during effortful listening.

Nevertheless, although a variety of short-term stressors have been shown to reliably raise levels of salivary cortisol and other stress-related chemicals (Skoluda et al., 2015), there has not yet been strong experimental evidence supporting a clear relationship between short-term listening challenges and increased levels of stress-related neurochemical responses. Kramer et al. (2016) report the results of a preliminary study comparing salivary levels of cortisol and chromogranin A (a chemical associated with the production of epinephrine and norepinephrine in the adrenal medulla) in listeners with hearing impairment and normally hearing listeners recognizing speech in noise. They observed a nonsignificant 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 (pretest) 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.

On the other hand, it is possible that the link between effortful listening and long-term stress is found not in the short-term activation of the SAM system in response to cognitive demands, but rather in the chronic activation of the HPA axis due to the interaction of short-term stressors and longer-term work expectations (Melamed, Fried, & Froom, 2001; Tafalla & Evans, 1997) and/or due to the psychosocial stress imposed by living with long-term communication challenges. There is some evidence that occupational noise exposure is more detrimental to cardiovascular health for those with cognitively demanding jobs (Melamed et al., 2001), and that correlates of HPA activation are more prevalent in noise-exposed listeners under high cognitive-demand conditions (Tafalla & Evans, 1997). Further, a few studies have suggested that cortisol levels, especially, are most strongly indicative of psychosocial stress (Skoluda et al., 2015), which is known to be higher in people with hearing impairment (Mackersie & Kearney, 2017; Pichora-Fuller, 2016). It is possible that physiological responses to demand on cognitive resources as such may not in itself have strong effects on stress neurochemistry, as suggested by the relatively small and unreliable effects observed thus far (e.g., Kramer et al., 2016) and thus may not directly affect long-term health. Nevertheless, the self-evaluative (affective) responses to the psychosocial burden imposed by chronic challenges to communication may still be quite significant in this regard. In other words, while it may turn out that listening effort defined as resource demand is not a direct cause of higher stress levels (and thus higher levels of stress-related neurochemicals), the negative self-evaluation and mood effects of the daily anticipation and experience of such effort and its psychosocial consequences very likely are (Pichora-Fuller, 2016).

## 4 | CONCLUSION

Listening effort has typically been characterized in terms of the deployment of limited capacity resources such as selective attention and working memory. Current models of resource allocation in speech perception suggest that there are two major domains of capacity demand. One involves more internally oriented capacity demand and is described as "filling in" mechanisms and "recalling from memory" by Shinn-Cunningham (2008), as the application of knowledge and expectations by Heald and Nusbaum (2014), or as domain general semantic/phonological processing in working memory in the ELU (J. Rönnberg et al., 2013). The other is focused on more signal- and auditory context-specific factors, and involves the application of selective attention in the service of parsing the auditory scene for object formation and selection (Edwards, 2016; Heald & Nusbaum, 2014; Shinn-Cunningham, 2008). Focusing on this distinction may facilitate the development of better, more targeted treatments for those individuals for whom listening effort represents a significant problem (Edwards, 2016). For example, directional hearing aids may improve source localization and the direction of selective attention (Desjardins, 2016; Picou, Moore, & Ricketts, 2017), cognitive training procedures may improve availability and allocation of limited resources in effortful listening contexts (Kuchinsky et al., 2014), and in the future, we may see benefits from even more direct interventions such as the application of targeted transcranial magnetic stimulation (Klimesch, Sauseng, & Gerloff, 2003; Luber & Lisanby, 2014).

However, despite the apparent practical and theoretical utility of distinguishing between these two levels of resource demand (Strauss & Francis, 2017), it remains to be seen whether they can be distinguished experimentally using established measures of listening effort. Moreover, it is not clear whether such a distinction is relevant for the assessment of listening effort as it pertains to listeners' subjective experience and ensuing decision-making. Closer examination of the behavioral and physiological measures employed to assess listening effort suggests an intrinsic, and possibly unresolvable, interaction between the commitment of processing resources on the one hand, and the affective response to their deployment on the other. Although this may complicate the interpretation of listening effort as an index of resource allocation alone, by linking the emotional response to resource demand via the concept of core affect, investigating listening effort from an integrated cognitive and affective perspective may also contribute to a better understanding of ways in which hearing impairment and working in noise may affect long-term health by increasing negative emotional interpretations of the affective consequences of effortful listening.

Anyone who has voluntarily run a marathon or climbed a mountain, done a sudoku or a crossword puzzle, or written a poem, composed music, or done any one of a million other effortful but ultimately rewarding activities knows that effort, itself, is not always unpleasant (Inzlicht, Shenhav, & Olivola, 2018; Kurzban, 2016) and, in the form of directing attention to address a challenge, may in fact be necessary for an experience to be truly fulfilling (Nakamura & Csikszentmihalyi, 2014). While it seems unlikely to us that the tasks that are typically employed in laboratory studies of listening effort (e.g., listening to speech in noise) would ever be considered desirable goals in themselves (e.g., like completing a crossword puzzle), simply determining that listening effort, even of a particular type, is required to complete a particular task does not tell the whole story. And, of course, there is an entire world of more naturalistic listening experiences that may prove to be desirable (at least to some individuals) not despite but actually because of their effortfulness.

We suggest that the integrality of signals reflecting cognitive resource deployment and affective response during effortful listening, and therefore the applicability of measurements associated with core affect to the assessment of listening effort, can be interpreted in terms of current theories of motivation as an allostatic mechanism (Touroutoglu et al., 2019). Motivation varies as the consequence of internal assessments of current and future resource capacities and needs (Touroutoglu et al., 2019) in order to promote (or inhibit) action to maximize survival (Bradley, 2009; Lang et al., 1997). It is often characterized in metabolic terms (Christie & Schrater, 2015; Fairclough & Houston, 2004), but can be equally applied to more abstract capacities and demands. Thus, the ongoing assessment of core affect (which one may become consciously aware of in the form of emotions, that is, "how do I feel" [Barrett, 2006; Craig, 2009]) serves to motivate attentional control (Cavanagh & Frank, 2014; Inzlicht et al., 2018) in the service of allostasis (Touroutoglu et al., 2019) and more generally, action to support survival (Bradley, 2009).

What makes listening effort something that is typically considered best to avoid, and what may make it ultimately potentially detrimental to health, seems to be the internal evaluation of the costs and benefits of exerting that effort for those goals in that context (Kurzban, 2016; Navon, 2013). Doing something that is "not worth the cost" (whatever that cost may be) is annoying, frustrating, and stressful and therefore potentially unhealthy (Matthen, 2016; McEwen, 1998). But such evaluation must surely be specific to individuals and contexts. Different people will have different thresholds for what they consider to be worth the cost in different circumstances. Therefore, the long-term consequences of effortful listening depend on listeners' evaluative (emotional) response to the circumstances that impose that effort as much as they do on the specific cognitive processing mechanisms engaged to address it. While it may be beneficial to distinguish between different loci of demand when considering how a particular task or context might impose effort, or how a particular treatment or remedy might mitigate it, it is essential to accurately measure and interpret the affective (hence emotional) aspects of listening effort in order to understand how listening effort affects communication-related decisions, such as whether to continue participating in a conversation in a noisy environment or whether or not to continue using one's hearing aid.

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## CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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