Hearing Impairment and Cognitive Energy: The Framework for Understanding Effortful Listening (FUEL)

M. Kathleen Pichora-Fuller,[1] Sophia E. Kramer,[2] Mark A. Eckert,[3] Brent Edwards,[4] Benjamin W.Y. Hornsby,[5] Larry E. Humes,[6] Ulrike Lemke,[7] Thomas Lunner,[8,9] Mohan Matthen,[10] Carol L. Mackersie,[11] Graham Naylor,[12] Natalie A. Phillips,[13] Michael Richter,[14] Mary Rudner,[8] Mitchell S. Sommers,[15] Kelly L. Tremblay,[16] and Arthur Wingfield[17]

The Fifth Eriksholm Workshop on "Hearing Impairment and Cognitive Energy" was convened to develop a consensus among interdisciplinary experts about what is known on the topic, gaps in knowledge, the use of terminology, priorities for future research, and implications for practice. The general term *cognitive energy* was chosen to facilitate the broadest possible discussion of the topic. It goes back to Titchener (1908) who described the effects of attention on perception; he used the term *psychic energy* for the notion that limited mental resources can be flexibly allocated among perceptual and mental activities. The workshop focused on three main areas: (1) theories, models, concepts, definitions, and frameworks; (2) methods and measures; and (3) knowledge translation. We defined *effort* as *the deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a task*, with *listening effort* applying more specifically when tasks involve listening. We adapted Kahneman's seminal (1973) Capacity Model of Attention to listening and proposed a heuristically useful Framework for Understanding Effortful Listening (FUEL). Our FUEL incorporates the well-known relationship between cognitive demand and the supply of cognitive capacity that is the foundation of cognitive theories of attention. Our FUEL also incorporates a motivation dimension based on complementary theories of motivational intensity, adaptive gain control, and optimal performance, fatigue, and pleasure. Using a three-dimensional illustration, we highlight how listening effort depends not only on hearing difficulties and task demands but also on the listener's motivation to expend mental effort in the challenging situations of everyday life.

Key words: Attention, Autonomic nervous system, Cognitive capacity, Cognitive energy, Effortful listening, Executive function, Fatigue, Listening effort, Hearing impairment, Motivation, Neuroeconomics, Stress, Working memory.

(Ear & Hearing 2016;37;5S–27S)

RATIONALE, SCOPE, AND PURPOSE OF THE WORKSHOP

Hearing, Cognition, and Motivation in Everyday Life: The Framework for Understanding Effortful Listening

The cornerstones of audiological assessment have always been pure-tone and speech audiometry. Speech audiometry typically includes measures of the threshold levels at which speech can be heard and suprathreshold measures of speech understanding such as percent-correct accuracy in recognizing standardized materials. However, as important as these measures are, more seems to be needed to evaluate the complaints made to audiologists by clients. They often report that sounds are loud enough and speech can be understood, but it is tiring and often just too hard to listen. Despite the frequently reported experience that listening is effortful, tiring, or stressful, even when sounds are audible and words are recognized accurately, clinical measures of listening effort have not been readily available. In the larger picture, how can audiologists better understand and find ways to counteract the factors underlying why listeners may decide to quit participating in activities because it takes too much effort to listen? How can audiologists help listeners to strategically deploy their available cognitive capacity in situations where it is hard to listen? How can audiologists prevent listeners from avoiding situations and withdrawing from social participation because it is too hard to listen?

Reports of effortful listening suggest that the difficulties experienced by listeners in their everyday lives depend on more than sounds simply not being audible or loud enough. Accordingly, solutions to their problems must extend beyond simply restoring the audibility of sounds. Listening may be effortful for those who have abnormal pure-tone thresholds, for those who have normal or near-normal audiometric thresholds but declines in suprathreshold auditory processing or cognitive processing (e.g., older adults), or for any person who participates in activities when the situation is acoustically adverse (e.g., noisy and reverberant) or informationally complex (e.g., multitasking). It seems that when the quality of auditory

---

[1]Department of Psychology, University of Toronto, Mississauga, Ontario, Canada; [2]Department of Otolaryngology–Head and Neck Surgery, Section Ear & Hearing and EMGO Institute for Health and Care Research, VU University Medical Center, Amsterdam, The Netherlands; [3]Department of Otolaryngology–Head and Neck Surgery, Medical University of South Carolina, Charleston, South Carolina, USA; [4]EarLens Corporation, Menlo Park, California, USA; [5]Department of Hearing & Speech Sciences, Vanderbilt Bill Wilkerson Center, Vanderbilt University School of Medicine, Nashville, Tennessee, USA; [6]Department of Speech & Hearing Sciences, Indiana University, Bloomington, Indiana, USA; [7]Phonak AG, Science & Technology, Cognitive & Ecological Audiology; Stäfa, Switzerland; [8]Linnaeus Centre HEAD, Swedish Institute for Disability Research, Department of Behavioural Sciences and Learning, Linköping University, Linköping, Sweden; [9]Eriksholm Research Centre, Oticon A/S, Snekkersten, Denmark; [10]Department of Philosophy, University of Toronto, Toronto, Ontario, Canada; [11]School of Speech, Language and Hearing Sciences, San Diego State University, San Diego, California, USA; [12]MRC/CSO Institute of Hearing Research, Scottish Section, Glasgow, United Kingdom; [13]Department of Psychology, Concordia University, Montreal, Quebec, Canada; [14]School of Natural Sciences, Liverpool John Moores University, Liverpool, United Kingdom; [15]Department of Psychology, Washington University, St. Louis, Missouri, USA; [16]Department of Speech and Hearing Sciences, University of Washington, Seattle, Washington, USA; and [17]Department of Psychology and Volen National Center for Complex Systems, Brandeis University, Waltham, Massachusetts, USA.

<zdoi; 10.1097/AUD.0000000000000312>

input is reduced, by impaired auditory abilities or by adverse acoustical environments, listeners may expend more mental effort to direct attention to and concentrate on one or more sound sources of interest. Individuals may also need to allocate more cognitive capacity to comprehend, remember, and respond to the auditory objects and events that they have perceived. Therefore, success in achieving listening goals may depend on the deployment of greater cognitive energy when the quality of the signal available to the listener is suboptimal. However, there is no guarantee that increasing cognitive energy will solve all listening problems. In some situations, when listeners are unable or unwilling to sustain a sufficiently high level of effort, they may experience fatigue and/or decide to quit the task at hand to avoid becoming fatigued. In other situations, the reward of immersive engagement in communication may have the opposite effect insofar as some listeners find that the intellectual and social benefits of listening and conversing increase motivation and add value to expending effort. In the long-term, if listening in everyday activities frequently demands more effort than listeners are able or willing to expend, they may develop chronic stress and withdraw from social interaction, with negative consequences to cognition, general health, well-being, and quality of life (Pichora-Fuller et al. 2015; Pichora-Fuller 2016, this issue, pp. 92S–100S).

It has often been stated that *we hear with our ears, but we listen with our brains*. In this consensus article, we build on the importance of auditory-cognitive connections by adding *and when and how much effort we expend during listening in everyday life depends on our motivation to achieve goals and attain rewards of personal and/or social value*. Our Framework for Understanding Effortful Listening (FUEL) incorporates the well-known relationship between cognitive demands and the supply of cognitive capacity that has been the foundation of prevailing cognitive theories of attention (Kahneman 1973). Our FUEL also incorporates ideas based on complementary theories of motivational intensity (Brehm & Self 1989), adaptive gain control and optimal performance (Aston-Jones & Cohen 2005), fatigue (Hockey 2013), and pleasure (Matthen 2016, this issue, pp. 28S–34S). By incorporating the effects of cognitive demands and motivation on effort, our FUEL provides a new way for audiologists to understand when and to what extent listeners expend effort in the challenging communication situations of everyday life.

Clinical Relevance of Auditory-Cognitive Interactions and Listening Effort

Over the past 2 decades and more, awareness has increased that auditory-cognitive interactions are important for listening in general (Handel 1989; Bregman 1990; McAdams & Bigand 1993; Neuhoff 2004) and speech understanding in noise in particular (CHABA 1988). Awareness has also grown regarding the important links between sensory and cognitive aging (Lindenberger & Baltes 1994; Baltes & Lindenberger 1997; Wingfield & Tun 2001; Humes et al. 2013; Albers et al. 2015). In this context, research in cognitive hearing science has flourished (Arlinger et al. 2009). Notably, psychologists and linguists have become interested in how well theories of cognitive and language processing based on the performance of normal young adults in ideal conditions generalize (or not) to account for their performance in adverse listening situations or for the performance of people who are younger or older or who have sensory impairments (e.g., Just & Carpenter 1992; Carpenter et al. 1994, 1995; Rönnberg et al. 2008, 2013; Mattys et al. 2012).

For audiologists, it has become clear that the development of more effective assessment and rehabilitation approaches requires a better understanding of cognition if the common complaints of patients are to be addressed. The need to take both auditory and cognitive factors into account was highlighted in the consensus article of the Third Eriksholm Workshop on *Candidature for and Delivery of Audiological Services: Special Needs of Older People*; specifically, the World Health Organization's International Classification of Functioning and Disability (ICF; WHO 2001) was used as a scaffold for discussing the auditory and cognitive aspects of age-related changes in hearing, listening, comprehending, and communicating (Kiessling et al. 2003). Since the 2003 Eriksholm consensus article was published, cognition has been implicated in a growing body of research investigating benefits from hearing aids. This research suggests that different types of signal processing algorithms seem to provide different mixtures of (dis)advantages to patients, according to their cognitive capacity (e.g., Davis 2003; Gatehouse et al. 2003, 2006a,b; Humes 2003, 2007; Humes & Wilson 2003; Lunner 2003; Humes & Floyd 2005; Foo et al. 2007; Lunner & Sundewall-Thorén 2007; Rudner et al. 2008, 2009, 2011; Arehart et al. 2013; Humes et al. 2013; Ng et al. 2013, 2015; Neher 2014; Souza et al. 2015; Ohlenforst et al. 2016).

From a hearing science perspective, laboratory research has provided convincing evidence that reduced cognitive performance on measures of memory and comprehension may be attributed, at least partially, to age-related declines in suprathreshold auditory processing. Specifically, age-related differences in suprathreshold temporal processing have emerged as one of the main characteristic of auditory aging across a range of psychoacoustic studies (for a review, see Fitzgibbons & Gordon-Salant 2010), with converging physiological evidence (e.g., Clinard et al. 2010; Anderson et al. 2012; Lopez-Poveda 2014). These changes in temporal auditory processing are thought to underpin problems understanding speech in noise and also remembering it once it has been heard. Notably, memory and comprehension performance is reduced in older adults who have elevated speech-in-noise thresholds, even if they are not obvious candidates for hearing aids because their audiometric thresholds are largely normal and they have relatively little difficulty in ideal, quiet listening situations (Schneider & Pichora-Fuller 2000; Pichora-Fuller 2003, 2006, 2007; Schneider et al. 2010).

From a population health perspective, epidemiological research has provided evidence of a significant association between hearing loss and incident dementia (Albers et al. 2015) and prompted questions regarding the potential advantages of adopting a more integrated approach to research on hearing health and cognitive health (Dupuis et al. 2015; Pichora-Fuller et al. 2015). Over the past decade, cognition has been introduced as a topic in practice guidelines for audiologists (Valente et al. 2006), in tutorial reviews for audiologists (e.g., Pichora-Fuller & Singh 2006), and in audiology textbooks (e.g., Pichora-Fuller 2013). Importantly, the imperative to find new clinical insights and better treatment solutions underpins the current willingness of audiologists to incorporate cognitive considerations into new best practices. This imperative also motivated our workshop.

In this era of cognition being introduced in audiology, audiologists have embraced the notion of listening effort. Listening effort seems to have good face validity because it is a theme of common complaints expressed by people who are hard of hearing. Perhaps even more importantly, hopes of being able to assess and offer technological, behavioral, and environmental treatments to reduce listening effort have created expectations for a revolutionary breakthrough in rehabilitative audiology. Such new approaches to rehabilitation would go beyond restoring audibility to make listening easier. The goal of such approaches would be to more fully meet the needs of people who have hearing problems and enable them to successfully achieve their participation goals.

Nevertheless, considerable confusion about the definition of listening effort has prevailed among audiologists and many are frustrated by not finding an easy or standardized method of measuring it (e.g., Rudner et al. 2012; McGarrigle et al. 2014). Without a clearer definition and a better understanding of listening effort, the pursuit of better interventions will likely be hampered. Without agreement about how to measure it, both assessment and outcome measurement are foiled. More generally, measuring the magnitude of the listening effort expended by a listener is not the only relevant issue. We also need to be able to assess how much effort a listener is motivated to expend. Without discovering the reasons why listeners persist or quit in challenging listening situations, it seems unlikely that we will understand how those who find listening too hard could find relief, let alone regain the pleasures of listening (see Matthen 2016, this issue, pp. 28S–34S). In part, this confusion in our field may have arisen because audiology curricula have not typically provided sufficient foundational knowledge about cognition. In part, it may also have arisen because relatively little research has investigated the generalizability of relevant psycholinguistic and cognitive theories to performance in adverse communication conditions or in people with sensory impairments. Furthermore, the topic of motivation has rarely been a focus of research in rehabilitative audiology. There is a clear need to overcome this confusion as we progress in translating knowledge from psychology to practice in audiology and in strengthening interdisciplinary and interprofessional collaborations.

Purpose of the Workshop

The Fifth Eriksholm Workshop on *Hearing Impairment and Cognitive Energy* was held in June 2015. The purpose of the Workshop was to come to a consensus about what is known on the topic, gaps in knowledge, the use of terminology, priorities for future research, and implications for practice in audiology. The general term *cognitive energy* was chosen for the name of the workshop to facilitate the broadest possible discussion of the topic. This term takes us back to Titchener (1908), a psychologist who described the effects of attention on perception; he used the term *psychic energy* for the notion that limited mental resources can be flexibly allocated among perceptual and mental activities (see Wingfield 2016, this issue, pp. 35S–43S). The workshop focused on three main areas: (1) theories, models, concepts, definitions, and frameworks; (2) methods and measures; and (3) knowledge translation. The 16 workshop participants included experts from different relevant disciplines, including audiology, engineering, neuroscience, speech perception, gerontology, philosophy, and many subfields of psychology spanning cognitive psychology, neuropsychology, motivational psychology, social psychology, and health psychology.

THEORIES, MODELS, CONCEPTS, DEFINITIONS, AND FRAMEWORKS

Audiologists would like to understand and be able to address the complaints of their clients that it is effortful to listen, even if sound is audible enough and words can be repeated with a high degree of accuracy. A reasonable place to begin in solving this puzzle is by considering which theories or models might be useful. The consensus developed at the workshop involved reviewing existing theories and models to evaluate how well they could account for available data on listening effort in people with normal hearing, people who are hard of hearing, and in special subpopulations, including bilinguals, healthy older adults, and older adults who have or are at risk for cognitive declines and dementia. Consistent with the views by Kuhn (1962) on scientific revolutions, we realized that our field is in a scientific crisis because no single existing theory or model is sufficient to solve the puzzle of listening effort for audiologists. At the core, our consensus calls for a paradigm shift by adapting and integrating concepts from different theories and models within our FUEL. Our hope is that our proposed FUEL will provide a more comprehensive account of the data and come closer to explaining the phenomenon of effortful listening for the purposes of informing future research and practice in audiology.

Theories and Models

The Workshop drew on two main types of theories and models, some concerning cognition, based primarily on behavioral findings, and some concerning motivation and arousal, based primarily on physiological findings.

Cognitive-Behavioral Theories and Models • One possibility is that the phenomenon of listening effort is simply a specific form of mental effort that occurs when a task involves listening. In the Third Eriksolm Workshop, listening was defined as hearing with intention and attention (Kiessling et al. 2003); that is, listening involves both auditory and cognitive processing. Not surprisingly, many of the experts who participated in the Fifth Eriksholm Workshop in 2015 approached the topic of listening effort by applying cognitive theories of attention, working memory and speed of processing, a trio of cognitive factors implicated in listening, speech understanding, and aging (for reviews, see Cohen 1987; CHABA 1988; see also Craik & Bialystok 2008). Importantly, for the purposes of our workshop, a historical overview of relevant cognitive theories provided the foundation for our deliberations (Wingfield, this issue, pp. 35S–43S). Workshop participants drew on cognitive theories to explain how hearing loss and age influence listening effort (Lemke & Besser 2016, this issue, pp. 77S–84S; Trembley & Backer 2016, this issue, pp. 155S–162S) and how the compensatory use of knowledge may influence listening effort in other special populations of listeners such as bilinguals and those who have cognitive impairments or dementia (Phillips 2016, this issue, pp. 44S–51S). Multimodal processing issues were considered in terms of the connection between cognition and sensory aging across modalities (Humes & Young 2016, this issue, pp. 52S–61S) and the cognitive demands of combining auditory and visual cues during speech understanding (Sommers & Phelps 2016, this issue, pp.62S–68S). It was also argued that cognitive processing during listening to speech, music, or environmental sounds could depend on the (lack of) availability of specific sorts of auditory cues that serve object formation and streaming, including binaural cues to spatial listening. Accordingly, a proposal was made (Edwards 2016, this issue, pp. 85S–91S) to integrate auditory scene analysis (Bregman 1990) into an existing cognitive model of language processing, the ease of language understanding model (Rönnberg et al. 2008). Reports on a series of experimental studies demonstrated the potential usefulness of new tests of working memory for evaluating the effects of hearing loss and hearing aid use on listening effort (Lunner et al 2016, this issue, pp. 145S–154S; Rudner 2016, this issue, pp. 69S–76S). In addition, an article from a social-cognition perspective considered how performance on auditory and cognitive measures may be modulated by factors such as stress, stigma, self-efficacy or social support that influence the appraisal of task demands, and self-perceived abilities to meet those demands during social participation in everyday life (Ryan et al. 1986, 1995; Chasteen et al. 2015; Pichora-Fuller 2016, this issue, pp. 92S–100S). Taken together, the consensus at the workshop was that cognitive theories and models were important and had been or could be applied to increase our understanding of auditory-cognitive connections.

Our consensus was to retain core aspects of previous cognitive theories and models and to interpret them in relation to research on listening effort and fatigue. In light of the numerous models proposed by cognitive psychologists over more than a half century, our consensus was that we would focus on principles that were common across models (see Wingfield 2016, this issue, pp. 35S–43S). The key principles of prevailing cognitive theories are that there is a limited capacity of mental resources that can be allocated to doing tasks, that there are individual differences in maximum capacity, and that the amount of capacity allocated to tasks increases as the tasks become more difficult or demanding (Wingfield 2016, this issue, pp. 35S–43S). As Wingfield notes, the first principle underlies current arguments that, when there is reduced hearing acuity or background noise, the perceptual effort needed for successful recognition of speech depletes available cognitive resources. When effortful listening depletes these resources, there may be insufficient resources remaining for encoding what has been perceived into knowledge stored in memory (Rabbitt 1968, 1990; Pichora-Fuller et al. 1995; Wingfield et al. 2005; Surprenant 2007) or for comprehending syntactically complex sentences (Wingfield et al. 2006). Thus, listening effort could be interpreted in terms of these theoretical principles concerning cognitive capacity.

It seemed to be most reasonable to adapt the seminal Kahneman (1973) Capacity Model of Attention for several reasons: it covers the breadth of issues we discussed at the workshop, it is based on a comprehensive consideration of prior models, and it has influenced subsequent models. Of note, Kahneman (pp. 189) assumes that effort is invested in perception. In particular, he suggests that when stimuli are recognized, "Activation is highest for a stimulus which has all the critical features, is presented at high intensity, and is attended. Inattention, degraded presentation, and a mismatch between the features of the stimulus and those of the recognition unit cause activation to decrease" (pp. 68). He emphasizes the importance of object or event formation and the binding of stimulus attributes when attention is allocated (pp. 105). These ideas resonate with more recently developed models related to listening, such as the ease of language understanding and auditory scene analysis models. Kahneman also seems to have anticipated several points in our current thinking about listening: (1) the distinction he makes between *sensory set* (i.e., input-related factors) versus *response* seems to be roughly compatible with what we might refer to today, respectively, as bottom-up versus top-down influences during comprehension; (2) his comments on the effects of response readiness can be related to current ideas concerning the role of priming and expectations in listening; and (3) his idea that there will be increased mental activity when demands are increased is compatible with the current notion of cognitive compensation (Pichora-Fuller 2010; Grady 2012).

Nevertheless, the nature of the relationship between the amount of capacity allocated and the task difficulty warrants more careful scrutiny. Crucially, what remains unexplained is how the allocation of cognitive capacity during listening may be modulated within and across individuals, even when the demands of the listening task have not exceeded a person's maximum capacity. Another perplexing issue, that had been noted by McGarrigle et al. (2014) and that also emerged at the workshop, is that there is not always agreement between subjective reports of listening effort (e.g., on a questionnaire) and behavioral measures (e.g., performance on a secondary task in a dual-task experiment). We still need to resolve what else influences self-reported listening effort and, at an extreme, we still need to explain why some people sometimes quit or disengage rather than persist in listening tasks.

Our consensus was that, in addition to accepting that cognition is important during listening, we need to go further to understand more fully the phenomenon of effortful listening. We were reminded of "conation." Conation is a concept from neuropsychology dating back over 200 years that has recently been revived. According to Reitan and Wolfson (2000), conation refers to the purposeful effort needed for task completion and, in neuropsychological terms, it is reflected by the ability to persistently focus one's mental energy on a task to achieve the best possible performance with speed and efficiency (Phillips 2016, this issue, pp. 44S–51S). Conation may provide a missing link between cognitive ability and the prediction of performance in everyday life and help to explain the imperfect relationship between measures of cognition and subjective measures of effort in the performance of a task (Reitan & Wolfson 2000). Although conation overlaps to some degree with the concepts of motivation and vigilance, it is thought to be a distinct and important factor in everyday problem-solving situations.

We were also reminded that the notion of *effort*, the role of arousal and motivation in attention, and the convergence or divergence of behavioral and physiological measures had already been featured in models of attention (Kahneman 1973; see also Wingfield 2016, this issue, pp. 35S–43S). For example, Kahneman (1973, pp. 113) observed that "distraction is resisted at a cost: motor tension and autonomic manifestations of arousal are higher than normal." More recently, Aston-Jones and Cohen (2005, pp. 105–106) described arousal as reflecting "a fundamental property of behavior that has proven difficult to define or to explain precisely with neurobiological mechanisms. The importance of arousal is undeniable: It is closely related to other phenomena such as sleep, attention, anxiety, stress, and motivation. Dampened arousal leads to drowsiness and, in the limit, sleep. Heightened arousal (brought on by the sudden appearance of an environmentally salient event or a strongly motivating memory) can facilitate behavior but in the limit can also lead to distractibility and anxiety."

Physiological Motivation and Arousal Theories and Models • Another possibility is that our understanding of the phenomenon of effortful listening would benefit from insights into the physiologic changes in the autonomic nervous system related to motivation and arousal that occur when a task involves listening. Workshop participants drew on a number of relevant theories and models and explored their past and potential future applications in the study of listening effort. Kahneman (1973, pp. 10) had recognized that "The key observation that variations of physiological arousal accompany variations of effort shows that the limited capacity [of the cognitive system] and the arousal system must be closely related." More specifically, he wrote (pp. 18) that "two standard measures of sympathetic activity remain the most useful autonomic indications of effort: dilation of the pupil is the best single index and an increase of skin conductance provides a related, but less satisfactory measure…. A third measure of sympathetic dominance, increased heart rate, cannot be used as a measure of effort, for reasons that will be described." Over 40 years later, the participants at our workshop considered current views on the measurement of listening effort using pupillometry (Kramer et al 2016, this issue, pp. 126S–135S), measures of skin conductance (Mackersie & Calderon-Moultrie 2016, this issue, pp. 118S–125S), and various cardiac responses (Mackersie & Calderon-Moultrie 2016, this issue, pp. 118S–125S; Richter 2016, this issue, pp. 111S–117S).

Kahneman (1973) also anticipated the use of evoked cortical potentials to measure the time-course of mental effort. Eckert et al. (2016, pp. 101S–110S) introduced the idea of neuroeconomics and reported on recent neuroimaging studies investigating the role of cingulo-opercular and frontoparietal brain areas in adaptive control during speech and language processing. These studies provide evidence that cingulate-opercular activity reflects how important success on a task is to a person (i.e., how the person evaluates success importance for a task; see also Brehm & Self 1989 and Richter 2016, this issue, pp. 111S–117S regarding *success importance*) in relation to motivation (see also Lee et al. 2012). Another workshop article, building on the research traditions of human factors engineering, provided an overview of how fatigue and mood or emotion may be related to the listening experiences of people who are hard of hearing (Hornsby et al 2016, this issue, pp. 136S–144S). Workshop participants also drew on a number of other scientific theories and models, including motivational intensity (Brehm & Self 1989), adaptive gain control and optimal performance (Aston-Jones & Cohen 2005), and fatigue (Hockey 2013). An article written from the perspective of a philosopher examined the notion of pleasure and used two contrasting cases to illustrate how expending effort could be facilitated by pleasure and how the net cost of listening is reduced when the person derives benefit or reward from listening; that is, even if the cost is a high allocation of effort, the value and importance of success can make it worthwhile to expend a high amount of effort (Matthen 2016, this issue, pp. 28S–34S). Taken together, the articles related to motivation, pleasure, and physiological measures of effort fill in important gaps in our understanding of when and to what extent individuals expend effort when engaging in the demanding activities of everyday life. Importantly, willingness to deliberately "spend" resources to attain success in achieving rewarding or meaningful goals seems to be a key to accounting for why people decide to engage (or not) in effortful listening. The thinking behind our FUEL was highly influenced by the notion that listening has a value and that listeners conduct a cost-benefit analysis to evaluate the net benefit from effort expended relative to the costs of or demands for the allocation of cognitive capacity (Brehm & Self 1989; see Matthen 2016, this issue, pp. 28S–34S; Richter 2016, this issue, pp. 111S–117S). These notions of cost-benefit analysis during listening were elaborated in our discussions regarding neuroeconomics (Eckert et al 2016, this issue, pp. 101S–110S), success importance (Richter 2016, this issue, pp. 111S–117S), and the potentially cost-mitigating effects of pleasure (Matthen 2016, this issue, pp. 28S–34S). Similarly, fatigue may hinge on motivation, and the control and management of goals insofar as expending effort can be fatiguing if goals are externally imposed but not when activities are self-initiated and meaningful (Hockey 2013; Hornsby et al 2016, this issue, pp. 136S–144S). Understanding the role of motivation and arousal in the choices made by listeners about how and when they engage (or not) in effortful listening takes us beyond the simple assumption that effort will go up as difficulty or demand for cognitive capacity goes up (see also Pichora-Fuller et al. 1998).

Concepts

We set out to understand the phenomenon or experience of effortful listening, as reported by people who are hard of hearing, so that we could find ways to measure it. We realized that it was unlikely that we could find a direct measure of "the hardness of hearing" (Matthen 2016, this issue, pp. 28S–34S). We did consider how various techniques had been used to measure a number of behavioral, physiological, or self-report responses from which inferences could be made about listening effort. We believed that we could make progress by identifying one or more concepts that would help to explain the phenomenon and that might help us to gain insight into why the various purported measures of listening effort diverge or converge.

We searched for one or more theories or models that we could use to account for the data before us. Following Kuhn's (1962) core idea that paradigm shifts occur when reconceptualization provides a better solution to the puzzle presented by the data, we struggled with whether *listening effort* was itself a concept or if it was a phenomenon that was explained by a collection of concepts that were somehow interrelated. Our conceptual struggles echoed those of Kahneman (1973, pp. 189) who asked "But a more significant aspect of this debate is conceptual: what is meant by saying that an activity requires or demands effort?" He also used a number of terms somewhat interchangeably, saying (pp. 8), "a capacity theory is a theory of how one pays attention to objects and to acts. In the present work, the terms 'exert effort' and 'invest capacity' will often be used as synonymous for 'pay attention'." Although Kahneman (1973) did not write about hearing loss, he did consider data from vision and hearing experiments and he dedicated a chapter to attention and perception. In the final chapter of his book, Kahneman considers perception and effort, saying (pp. 189): "The occurrence of perceptual deficit during mental activity provides the most direct evidence for the relation between perception and effort. If an activity can be carried out without effort, it should no more be subject to capacity interference than be the source of such interference. Indeed, the most sensitive test of whether an activity demands effort is whether it can be disrupted by intense involvement in another activity. An act that demands little effort may be vulnerable to interference, while having negligible effects on other acts." As described earlier in the section on auditory-cognitive interactions, over the intervening decades since Kahneman wrote his book, research has provided evidence that auditory processing difficulties, hearing loss, and noise do indeed disrupt memory, confirming that listening with suboptimal auditory input can meet Kahneman's test for whether or not an activity demands effort. Next, we elaborate on the definitions of effort and fatigue and other key terms that were endorsed in our consensus.

Definitions: Effort and Fatigue

The workshop participants discussed how to define the key terms *effort* and *fatigue*. They also contributed definitions of other key terms used in their articles. During and after the workshop, these definitions were honed to achieve consensus and consistency in the terminology used across articles to the extent that this was possible. Definitions of the primary concepts are listed in Table 1, including mention of synonymous and alternative or related terms. The secondary terms based on the primary terms are listed in Table 2.

In a recent white paper, the British Society of Audiology (BSA) Special Interest Group on Cognition in Hearing gave "the mental exertion required to attend to, and understand, an auditory message" as their working definition of listening effort based on dictionary entries (McGarrigle et al. 2014, pp. 434). According to the BSA group, agreement has not been reached about a standard definition of listening effort; however, they noted that a number of audiologists have used the term to refer to the attentional and cognitive resources required to understand speech (Hicks & Tharpe 2002; Anderson Gosselin & Gagné 2011; Fraser et al. 2011; Picou et al. 2011). The BSA group questioned if restricting the definition of listening effort to speech was overly narrow because listening to music or environmental sounds might also be effortful. They also pointed out that listening could become more effortful in adverse conditions for speech recognition but that listening could become less effortful if visual cues were available to the listener. The BSA group adopted the classification of adverse conditions for speech recognition used in the review by Mattys et al. (2012). This classification is similar to the well-known speech chain model (Denes & Pinson 1963; for an updated version including visual speech, see Humes & Bess 2013), whereby reductions in the quality of the speech signal being relayed could be attributed to factors related to the talker (e.g., talkers might have accents), the transmission (e.g., transmissions could be affected by noise, reverberation, or alterations of the signal by intervening technologies such as hearing aids), or the listener (e.g., listeners might have hearing loss).

The approach of our workshop group was to begin by adopting a more generic definition of *mental effort* as *the deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a task*. The generic definition of mental effort could be specified such that *listening effort* is simply effort involved in carrying out listening tasks. In agreement with the BSA group, our workshop consensus was that listening effort should extend beyond listening to speech to include intentional listening to any auditory source, including music and environmental sounds. Furthermore, for the purposes of our workshop, listening was considered in the broadest possible terms to extend from listening in artificial laboratory conditions to listening in the naturalistic conditions of everyday life. In contrast to listening in artificial laboratory conditions, listening in ecologically realistic conditions would likely entail binaural rather than only monaural listening, occur with multimodal rather than only auditory input, and involve the use of a wide range of contextual cues and linguistic and world knowledge.

Effort measured in the laboratory is likely to differ from effort experienced in the real world because of differences in the duration of tasks. Change in effort over time may be less apparent over the course of a relatively brief testing session in the laboratory than over the course of a day in a listener's life. There could be cumulative effects of recurring episodes of effortful listening over days and years in a listener's life. In addition, we recognized that the experience of effort in the moment might be modulated by the listener's appraisal of future or long-term demands and the consequences of succeeding in the immediate task.

Consideration of the time course over which the person expends effort prompts consideration of "fatigue." According to Hornsby et al. (2016, this issue, pp. 136S–144S), fatigue is a complex construct with a definition that varies depending on who uses the term (e.g., layperson, physiologist, cognitive psychologist, and physician) and the focus of their interest (e.g., physical fatigue in athletes, cognitive fatigue in individuals who have multiple sclerosis, and emotional fatigue in those who have depression). The article by Hornsby et al. (2016, this issue, pp. 136S–144S) reviews definitions and concepts from the broader fatigue literature and their relation to hearing (loss). Historically, fatigue has been defined as a mood state or subjective experience, and it has been measured in terms of fatigue-related performance decrements. Subjective fatigue is defined as a subjective experience or mood state that may manifest as feelings of weariness, tiredness, a lack of vigor or energy, or decreased motivation to continue doing a task. Transient or acute fatigue is due to the mental (and/or physical) demands of a given situation, whereas long-term fatigue is constant or recurrent and not necessarily due to specific transient events or situations. General fatigue is a general sense or feeling of being tired, worn out or sluggish, having low energy or motivation to complete at task; it may be caused by various underlying factors or mechanisms (e.g., sleep loss, medications, disease, or sustained physical or mental work). Mental fatigue and physical fatigue correspond to reduced ability, or desire, to perform mental or physical tasks. Mental fatigue is often associated with self-perceived or objectively measured difficulties with concentration, attention, clear thinking, or memory. Likewise, physical fatigue pertains to difficulties performing physical tasks, often as a result of sustained physical exertion or as a consequence of disease. Importantly, Hockey (2013) argues that the subjective fatigue experience serves an adaptive, goal-directed, function by forcing us to evaluate our current behaviors in terms of the effort required to achieve a reward from completion or continuation of a task. Should the effort-reward relationship be unfavorable, motivation to continue toward a given goal may be reduced. These general definitions and views of fatigue could be adapted such that *listening fatigue* is simply fatigue resulting from the continued application of effort during difficult listening tasks.

If fatigue is a lack of energy, then how is *energy* defined? From the perspective of physics, energy is the capacity to do work. With respect to humans, fatigue and energy are both mood states. In general, energy, vigor, and vitality are the same or similar, and being or feeling energetic has been described in various assessment tools as being or feeling active, vigorous, lively, or full of

TABLE 1. Definitions of Primary Concepts Referred to in Papers in This Special Issue

Term	Description	Paper(s)
Attention	A multidimensional construct that includes orienting, selecting, and/or focusing on environmental stimuli (e.g., speech) or internal *representations* (e.g., thoughts) for varying periods of time.	Eckert et al.; Phillips
Arousal	A fundamental property of behavior, related to phenomena such as sleep, *attention*, anxiety, stress, and motivation. Dampened arousal leads to drowsiness and, in the limit, sleep. Heightened arousal (brought on by a salient event or a motivating memory) can facilitate behavior but in the limit can also lead to distractibility and anxiety.	Aston-Jones & Cohen (2005), cited in Pichora-Fuller et al.
Effort	The deliberate allocation of *resources* to overcome *obstacles* in goal pursuit when carrying out a *task.* This definition of effort is consistent with Kahneman's (1973) notion of effort as the capacity supplied to meet the capacity demanded when a person performs a task.	Pichora-Fuller et al.
Energy or vigor or vitality	A subjective mood or feeling of being able to do physical or mental *work*. Energy, vigor, and vitality are the same or similar constructs.	Hornsby et al.
Fatigue	Fatigue is a complex construct that must be explicitly defined based on the discipline of the person describing the construct and the focus of their study (e.g., physical fatigue in athletes, cognitive fatigue in people with multiple sclerosis, general fatigue, or vigor deficits in people with hearing loss). It is commonly described as a feeling/mood state or in terms of a decrement in physical or cognitive performance.	Hornsby et al.
Listening effort	A specific form of *mental effort* that occurs when a task involves listening.	Pichora-Fuller et al.
Mental effort or processing effort	The deliberate allocation of mental *resources* to overcome *obstacles* in goal pursuit when carrying out a *task.*	Pichora-Fuller et al.
Motivation	Approach motivation: the energization of behavior directed toward positive or desirable stimuli. Avoidance motivation: energization of behavior directed away from negative or undesirable stimuli. Sometimes motivation is referred to as engagement.	Elliot (2013), cited in Kramer et al.
Obstacles	Factors that make the completion of a *task* more difficult.	Matthen
Resources	Means available for the execution of *tasks*. The terms "cognitive resources," "processing resources," "attentional resources," and "resources" are often used interchangeably.	Wingfield
Self-efficacy	Refers to "beliefs in one's capabilities to organize and execute the courses of action required to produce given attainments."	Bandura (1997, pp. 3), cited in Pichora-Fuller
Social support	Refers to the perceived quality, rather than the quantity, of relationships providing emotional or affective support, instrumental support (e.g., material or financial support), and/or informational support.	Cohen (2004), cited in Pichora-Fuller
Stereotype threat	Refers to being at risk of confirming, as self-characteristic, a stigmatizing aspect of identity based on one's group (e.g., age group), often resulting in underperformance on tasks.	Pichora-Fuller
Stress	An individual's total response (physiological, cognitive, emotional) to environmental demands or pressures. Stress occurs when there is an imbalance between the person and his or her environment; i.e., when the demands of a situation are perceived as straining or exceeding capacities, thereby threatening well-being.	Pichora-Fuller
Task	A goal that a person might try to achieve. The goal is specified in terms of an array of necessary states, which should be attained, including eventual constraints (e.g., when, in what sequence, states to be avoided).	Matthen
Task demands	The cognitive and perceptual *resources* needed to complete a *task*. This may refer to total resource demands or the resources needed at a given point in the task to maintain successful task execution (which may change over time). Note that the true task demands (total or momentary) may differ from those estimated by a person.	Mackersie & Calderon-Moultrie
(Net) Value	The benefit of an action or situation minus its cost. Net value can be negative.	Matthen
Work	A series of actions performed to complete a *task*. Work consumes *resources*.	Matthen
Working memory (WM)	The retention of information in conscious awareness when this information is not present in the environment, for its manipulation and use in guiding behavior.	Postle (2006), cited in Wingfield

Terms defined elsewhere in Tables 1 or 2 are shown in italics.

TABLE 2. Secondary Terms Related to the Primary Terms Shown in Table 1

Term	Description	Paper(s)
Adaptive control	The monitoring of outcomes and *task demands* to adjust behavior with the goal of optimizing performance or reward.	Eckert et al.
Cognitive bias	A mental attitude that systematically assigns greater *value* to one type of situation or action over another	Matthen
Cognitive fatigue	Sometimes used to refer specifically to *fatigue*-related performance decrements on cognitive *tasks*. See also *mental fatigue*.	Hornsby et al.
Cognitive load or mental load or processing load	The extent to which the *demands* imposed by the *task* at a given moment consume the *resources* available to maintain successful task execution.	Lemke & Besser
Cognitive reserve	An individual's ability to withstand the cognitive effects of brain pathology	Phillips
Cognitive spare capacity (CSC)	During the successful execution of a primary cognitive *task* (e.g., *word recognition*), CSC is the extent of unused cognitive *resources* or *capacity* available for other tasks (e.g., comprehension or recall of what was heard).	Rudner
Compensation	The use of additional neural systems to help a domain-specific system (e.g., auditory system) engaged in a *task*.	Eckert et al.
Conation	The ability to apply purposeful and sustained *effort* to focus one's intellectual *energy* on a *task* to achieve the best possible performance.	Phillips
Cost/benefit	The negative (cost) or positive (benefit) components of the *value* to a person of a particular action (or its omission). Costs and benefits are meant as commensurate, so that costs can be subtracted from benefits.	Matthen
Divided attention	The use of *attentional resources* to process two or more *tasks* or sources of information simultaneously (or in rapid, alternating succession)	Phillips
Dual-task paradigm	A test paradigm used to measure *divided attention*; participants are asked to perform *Task* A and Task B individually and also concurrently; the change in performance in the concurrent condition is taken to indicate the cost of dividing attention.	Phillips
Effortful listening	An act of listening that involves *effort*.	Pichora-Fuller et al.
Effort discounting	The idea that an object or experience loses *value* as the amount of *effort* that is required to obtain the object or experience increases.	Eckert et al.
Emotional fatigue or affective fatigue	Also referred to as affective fatigue; A reduced ability or desire to perform physical or mental *tasks* resulting from the emotional or psychological demands of others or a given situation.	Hornsby et al.
Encoding	The process by which the trace in *short-term memory* evoked by an external stimulus is consolidated into *long-term memory*.	Lunner et al.
Episodic long-term memory	Organized mental representations of personally experienced episodes.	Rudner
Executive function	The strategic control of mental processes.	Rudner
Explicit processing	Strategic control of access to *working memory* by *executive function*.	Rudner
Free recall paradigm	A test paradigm in which a set of to-be-remembered items is presented to a person for later recall in any order in the absence of any retrieval cues.	Lunner et al.
Future discounting	A cognitive bias that reduces the estimated *value* of situations more vs. less distant in the future.	Matthen
Inhibitory control or Inhibition	The suppression of irrelevant stimuli and/or mental representations in *working memory*, to focus attention on *task*-relevant information.	Eckert et al.
Mild cognitive impairment (MCI)	A clinical syndrome in which there is nonacute decline in one or more cognitive domains but which does not result in functional impairment.	Phillips

(*Continued*)

TABLE 2. Continued

Term	Description	Paper(s)
Memory recall paradigm	A test paradigm that includes both encoding in memory of a list of items-to-be remembered and the subsequent retrieval of the stored memory.	Lunner et al.
Mental fatigue	A reduced ability (a performance decrement) or desire (a subjective feeling or mood) to perform mental or cognitive processes or *tasks*. Often associated with perceived or measured difficulties with concentration, *attention*, clear thinking, and memory.	Hornsby et al.
Mismatch	Failure of rapid and automatic binding of language input to existing *representations* in semantic *long-term memory*.	Rudner
Motivational harmony	A situation in which a person enjoys *effort* (E) that leads to benefit (B), with the result that the net *value* of E is greater than that of its consequential benefit B (i.e., the effort itself is experienced as having a positive value).	Matthen
Neuroeconomics (of listening)	The study of neural systems that contribute to the decision or intention to perform a *task* (e.g., listen), consider alternative behavioral options (e.g., not listen), and plan a course of action to improve behavior or perception.	Eckert et al.
Parasympathetic withdrawal	A reduction of parasympathetic nervous system activity.	Mackersie & Calderon-Moultrie
Perceived effort	Subjective experience of how taxing a *task* is or was.	Lemke & Besser
Perceptual load	The degree to which *selective attention* processes are required to exclude distracting sensory information.	Phillips
Peripheral fatigue	A difficulty initiating or maintaining some physical *tasks* due to limitations in peripheral processing abilities (i.e., cellular, circulatory or neuromuscular limitations).	Hornsby et al.
Physical fatigue	A reduced ability (a performance decrement) or desire (a subjective feeling or mood) to perform physical *tasks*. This type of *fatigue* is generally the result of sustained physical exertion or the consequence of a disease process.	Hornsby et al.
Pleasure	A conscious mental state that leads to estimating a state of affairs as a benefit. Pleasure creates value. If an action is pleasurable, its estimated net value increases, and it may become a net benefit.	Matthen
Processing speed	The rate at which information is treated or an operation is performed in the perceptual-cognitive system; considered a fundamental cognitive *resource*.	Phillips
Pupillometry	The continuous recording of the pupil diameter.	Kramer et al.
Reactivity	Change in physiological activity during a *task* relative to a specified reference condition.	Mackersie & Calderon-Moultrie
Reading span test or listening span test	A *working-memory* test designed to tax memory storage and processing simultaneously as a person reads or listens to and judges sets of sentences presented in increasing set sizes. The span measure resulting from a reading (or listening) span test is the largest set size for which all target items were recalled correctly. Higher values indicate greater *working memory capacity*.	Daneman & Carpenter (1980), cited in Lunner et al.
Recall measure	Recall is often measured as the proportion of encoded events or items of information that are correctly retrieved.	Lunner et al.
Representation	Memory traces of perceptual experiences, rehearsals, or thoughts.	Rudner
Selective attention	The focusing of *attention* on some aspect(s) of a stimulus input and the inhibition of other aspects.	Phillips
Short-term memory (STM)	A “buffer” memory whose primary function is to hold newly arriving information temporarily until it can be transferred (“consolidated”) by rehearsal into *long-term memory* (LTM).	Broadbent (1958), cited in Wingfield
Social evaluative threat	Fear of negative evaluation by others.	Mackersie & Calderon-Moultrie

(*Continued*)

TABLE 2. Continued

Term	Description	Paper(s)
Sound aversion	Negative emotional reaction to sound	Mackersie & Calderon-Moultrie
Speech understanding or recognition or identification	The recognition or identification of open- or closed-set speech materials to the extent that the listener would be able to repeat the material. Unlike comprehension, understanding does not necessarily require higher-level (e.g., semantic) processing of the material.	Humes & Young
Subjective fatigue	A subjective experience or mood state, encompassing feelings of weariness, tiredness, lack of *vigor* or *energy*, or decreased *motivation* to continue a *task*. Subjective fatigue can result from a wide range of factors, including sustained physical or mental effort, emotional distress, sleep disturbance, and physical or mental disease processes.	Hornsby et al.
Task engagement	Readiness to invest *resources* to accomplish a *task* goal. Thus, task disengagement implies a rejection of the task, at least for the time being. See also *motivation*.	Lemke & Besser
Updating	The strategic addition of new information to *working memory* at the expense of old information.	Rudner
Working memory capacity (WMC)	A finite capacity that constrains the amount of cognitive operations that can be carried out in *working memory*. WMC varies among individuals.	Wingfield

pep (Hornsby et al 2016, this issue, pp. 136S–144S). It is possible that fatigue is related to a decrease in the efficiency or availability of cognitive resources (Gergelyfi et al. 2015). Although fatigue is often negatively associated with energy, motivation to engage in a particular task may also be important, as is suggested by findings that people may experience fatigue for one task, but still have high energy for another task, and that the symptoms of fatigue may be reduced following a purely motivational intervention. This latter point also suggests that the relationship between fatigue and motivation could be bidirectional, such that fatigue may modulate motivation and vice versa. Thus, whether we consider effort or fatigue, it seems that we need to incorporate a motivational arousal dimension in our framework. Note that both energy level and motivation are included in the ICF (WHO 2001) comprehensive core set for hearing loss (Danermark et al. 2013; ICF Research Branch 2013): Energy level (b1300) refers to mental functions that produce vigour and stamina, and Motivation (b1301) refers to mental functions that produce the incentive to act, the conscious or unconscious driving force for action.

Frameworks

Theories, models, and frameworks can serve various purposes. According to Borg et al. (2008, pp. S131), "[A] model is defined as a set of related concepts that can quantitatively predict an outcome on the basis of certain premises. The framework is a series of defined concepts that are less precisely related and that are not formulated in a way that allows quantitative testing." Our consensus was that, given the current state of knowledge in audiology about effortful listening, it was more reasonable to propose a conceptual framework, rather than a model, because we are not yet at a stage where we could quantitatively predict outcomes. Furthermore, as described earlier, there is an abundance of existing models pertaining to cognitive effort (see Wingfield 2016, this issue, pp. 35S–43S), and it seemed unnecessary to attempt to create yet another model for effortful listening that, for the most part, would incorporate the same core ideas that had already been promoted in prior models. In the interests of facilitating research and reducing confusion in the emerging audiology literature concerning listening effort, our consensus was that our FUEL should adapt and integrate several relevant conceptual dimensions based on multiple existing models. Our consensus was that the new framework could facilitate the future development of a model that could be used to quantify listening effort in audiology.

FRAMEWORK FOR UNDERSTANDING EFFORTFUL LISTENING

As mentioned earlier and described in more detail later, our FUEL is an adaptation of Kahneman's (1973) model. Figure 1A is a reproduction of Kahneman's original Capacity Model of Attention (1973; Figure 1.2, pp. 10). As depicted in Figure 1A, the core components of his capacity model are the tank of "available capacity" shown as fluctuating with "arousal" and the "allocation policy," which governs how much of the available capacity will be supplied to which activities. According to Kahneman (1973, pp. 11), the allocation policy "is controlled by four factors: 1) Enduring dispositions which reflect the rules of involuntary attention (e.g., allocate capacity to any novel signal; to any object in sudden motion; to any conversation in which one's name is mentioned); 2) Momentary intentions (e.g., listen to the voice on the right earphone; look for a redheaded man with a scar); 3) The evaluation of demands….; 4) Effects of arousal." These four factors are shown as having arrows going to the allocation policy component shown in Figure 1A. Furthermore, he states that "The level of arousal is controlled by two sets of factors: 1) the demands imposed by the activities in which the organism engages, or prepares to engage; and 2) miscellaneous determinants, including the intensity of stimulation and the physiological effects of drugs or drive states" (pp. 17). These two factors are shown with arrows going to arousal. There are also two outputs. The main output labeled "responses" is shown at the bottom of the figure and represents

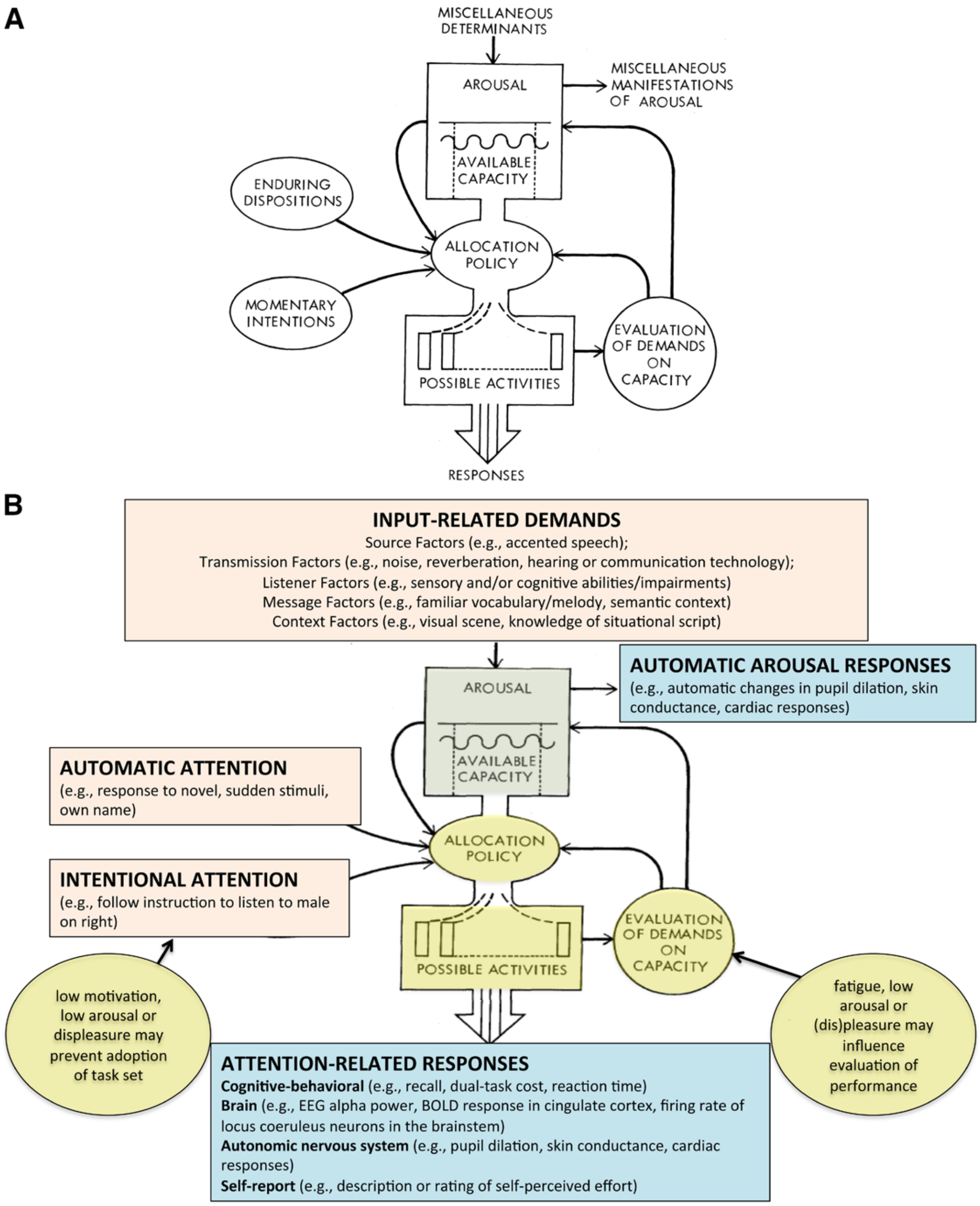

Fig. 1. Interpretation of Kahneman's (1973) Capacity Model for Attention in relation to listening effort and fatigue. A, Kahneman's Capacity Model of Attention (borrowed with permission from Kahneman 1973, Figure 1.2, pp. 10). B, Our interpretation of Kahneman's (1973) model in relation to effortful listening. B preserves the original component from A showing available cognitive capacity varying with arousal (colored light green). Also preserved are the core evaluation components shown in yellow: the evaluation of demands on capacity, the allocation policy, and the possible activities to which capacity is allocated. The two bubbles colored yellow are adapted from Kahneman's Figure 3.3 (1973, pp. 36) in which he introduces these components to show the effects of high and low arousal on attention and performance. We have added (dis)pleasure to these two bubbles. We have also changed his word "interfere" to "influence" because fatigue and (dis)pleasure can influence the evaluation of performance without being the results of performance. For example, some current models (e.g., Hockey 2013) suggest that the subjective (unpleasant) experience of fatigue may actually be a trigger that encourages the individual to evaluate the benefits of successful performance relative to the effort required to achieve, or maintain, that performance. Similarly, (dis)pleasure can predispose effort insofar as pleasure in anticipation of and during performing a task can be motivating (Matthen 2016, this issue, pp. 28S–34S). Salmon-colored boxes include direct inputs to the allocation policy or indirect inputs via the cognitive capacity component. The original label "enduring dispositions" has been replaced with "automatic attention," "momentary intentions" with "intentional attention," and "miscellaneous determinants" with "input-related demands." The examples for the two attention components are the same as those provided by Kahneman (1973). The examples for input-related demands are an elaboration of Kahneman's example of "intense stimulation" (1973; Figure 2.2, pp. 18) and are tailored to stimulus, individual, and environmental factors pertinent to effortful listening. Blue-colored boxes are for responses or outputs from Kahneman's model. We have replaced "miscellaneous manifestations of arousal" with "automatic arousal responses," but the examples are consistent with those of Kahneman's (1973, Figure 2.2, pp. 18). Where the original Kahneman (1973) model simply indicates "responses," we have elaborated these and renamed the component of the model "attention-related responses."

the result of capacity having been allocated to one or many possible activities. There is also another output labeled “miscellaneous manifestations of arousal.”

Figure 1B is an adaptation of Figure 1A to show how our FUEL is an interpretation of Kahneman’s model in relation to listening effort. The original core component from Figure 1A is shown in green in Figure 1B as the available cognitive capacity varying with arousal. Also preserved are the core evaluation components shown in yellow: the evaluation of demands on capacity, the allocation policy, and the possible activities to which capacity is allocated. We did not alter the core components, but we note that the allocation policy (i.e., executive function) may also require the allocation of resources, especially in multitasking situations.

Figure 1B also includes some elaborations provided in Kahneman’s other figures. Specifically, the two bubbles colored yellow are adapted from Kahneman’s Figure 3.3 (1973, pp. 36) in which he introduces these components to show the effects of high and low arousal on attention and performance. We have added (dis)pleasure to these two bubbles. We have also changed his word “interfere” to “influence” because current thinking is that fatigue and (dis)pleasure can influence the evaluation of performance without being the results of performance. Some current models (e.g., Hockey 2013) suggest that the subjective (unpleasant) experience of fatigue may actually be a trigger that encourages the individual to evaluate the benefits of successful performance relative to the effort required to achieve, or maintain, that performance. Similarly, (dis)pleasure can predispose effort insofar as pleasure in anticipation of and during performing a task can be motivating (Matthen 2016, this issue, pp. 28S–34S). Importantly, the effects of arousal or motivation level on performance could offer an account for quitting even when the available capacity supply has not been exceeded by the demand for capacity.

Salmon-colored boxes in Figure 1B include direct inputs to the allocation policy or indirect inputs via the cognitive capacity component. We modified the labels of these components. Consistent with Kahneman’s explanation of the labels “enduring dispositions” and “momentary intentions,” we use the labels “automatic attention” and “intentional attention,” respectively, because these terms seem to be easier to relate to the study of listening effort; however, the examples for the two attention components given in Figure 1B are the same as those provided by Kahneman (1973). We relabeled his “miscellaneous determinants” as “input-related demands.” Our examples for input-related demands expand on Kahneman’s example of intense stimulation as a miscellaneous determinant of arousal (1973; Figure 2.2, pp. 18) and are tailored to stimulus, individual, and environmental factors pertinent to effortful listening. These input-related demands include those recognized as contributing to adverse listening conditions, namely factors affecting the quality of the source signal, signal transmission, and listener abilities (as discussed earlier; for a review, see Mattys et al. 2012). Here, however, they are expanded to align with the Speaker-Listener-Environment-Message model used in rehabilitative audiology that includes message-related linguistic and contextual factors (e.g., Erber 1988; Robertson et al. 1997).

Blue-colored boxes in Figure 1B indicate responses or outputs similar to Kahneman’s model. We have replaced the label

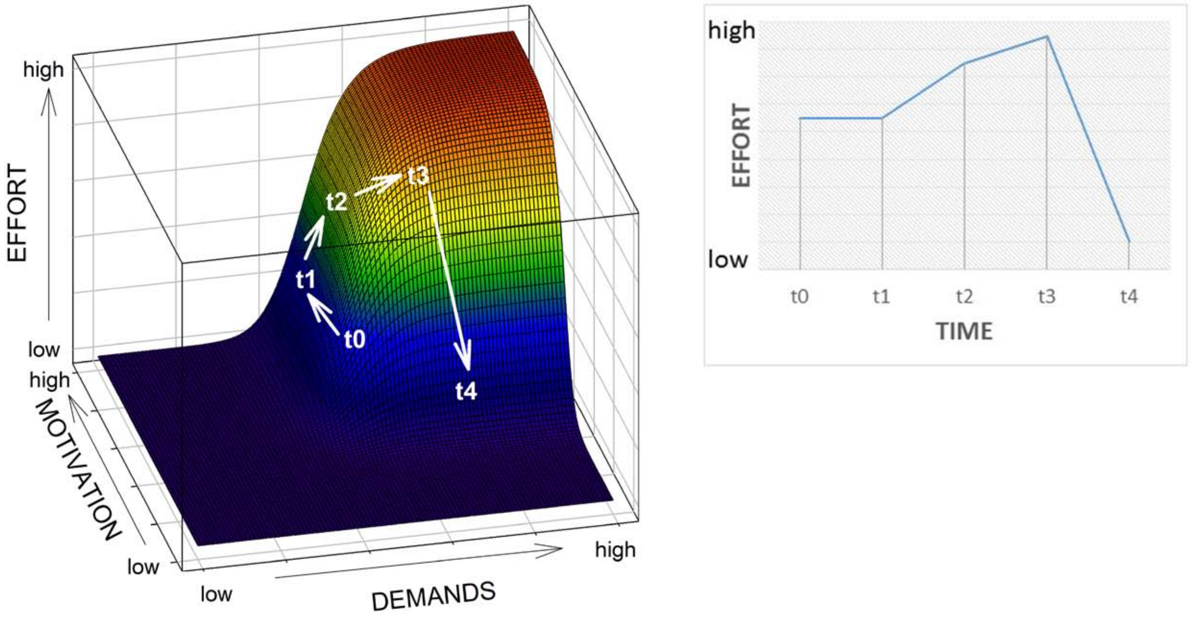

Fig. 2. The three-dimensional (3D) plot illustrates how effort may vary as a function of the demands for capacity needed to perform an activity and the motivational arousal of the person. The Effort, Demands, and Motivation axes show scales from low to high; however, no units are specified. Superimposed on the 3D plot is an illustration of how the effort expended by a person might change over the time course of an activity as a function of both demand and motivation. For example, over the course of an activity, demand could vary due to changes in the level of background noise and motivation could vary due to changes in the person’s evaluation of the importance of success in performing the activity. The following changes are reflected in the segments: T0 to T1 shows demand held constant but increasing motivation as engagement in the task ramps up (e.g., the ambient noise level is constant but the topic of conversation turns to a highly interesting story); T1 to T2 to T3 shows motivation held constant but demand increasing and a corresponding increase in effort (e.g., the conversation continues to be highly interesting but the level of background noise increases as more people arrive at the party); T3 to T4 shows demand held constant but as motivation is reduced there is a decrease in effort (e.g., the level of background noise remains steady but the highly interesting story finishes and the conversation turns to a less interesting topic). The panel showing changes in effort over time corresponds to the three segments shown on the 3D figure.

"miscellaneous manifestations of arousal" with "automatic arousal responses," but the examples are consistent with Kahneman's (his Figure 2.2, pp. 18, 1973). Specifically, Kahneman indicates that the miscellaneous manifestations of arousal would include automatic responses such as pupillary dilation, increased skin conductance, and changes in heart responses. Finally, where the original Kahneman (1973) model simply indicates "responses," we renamed the component of the model "attention-related responses." We elaborated by adding examples of measures (cognitive-behavioral, brain, autonomic nervous system, and self-report) that could be used to index attention-related responses. These responses are candidates for measuring listening effort insofar as they support inferences regarding the allocation of capacity or the expending of effort.

Importantly, Kahneman (1973) recognized the need to understand effort in terms of cognition and motivational arousal. In keeping with that outlook, we developed a three-dimensional (3D) figure (Fig. 2) to depict how effort might be related to demands and also to motivation. Our Figure 2 is based on two figures from Kahneman's book. First, our Figure 1 was influenced by Kahneman's Figure 2.1 (pp. 15) that plots effort as the capacity supplied as a function of the capacity demanded by a task. Second, his Figure 3.2 (pp. 34) also influenced our Figure 2. His Figure 3.2 shows how the quality of performance varies nonlinearly with arousal level (based on Yerkes & Dodson 1908), such that performance can be reduced for either very low or very high arousal levels but with the specific nature of the function depending on the complexity of the task. Furthermore, in our Figure 2, we have innovated by plotting motivation as a third axis to illustrate how the effort expended might vary (according to the allocation policy) with both the demands and the motivation dimensions. The demand dimension would depend on input-related demands (e.g., signal properties, hearing loss) and task demands based on automatic (e.g., default monitoring of the environment) and intentional attention factors (e.g., instructions). The motivation dimension would depend on how arousal or fatigue may influence the individual's evaluation of the importance of success and the value of expending resources to meet demands on capacity. The axes for effort, demands, and motivation range from low to high; however, the units are unspecified. Notably, there is no agreement as to what would be an appropriate scale for any of the three dimensions, nor do we yet understand exactly how motivation and demands might interact to influence effort. In general, however, consistent with the views of Kahneman, it seems that there is potential for the measurement of effort to be compatible with a more traditional signal-detection approach. Although the shape of possible functions is unknown, for illustrative purposes, the motivation and demand dimensions are based on somewhat arbitrary sigmoidal functions using a four-parameter logistic model (Equation 1 with A = 0, B = 10, C = 0.5, and D = 1) consistent with typical psychometric functions.

$$y = ((A - D) / (1 + ((x / C)^B))) + D \tag{1}$$

A key advantage to depicting three dimensions is that some methods for assessing effort may be more sensitive to factors related to the nature of the sensory input or to task demands while other measures may be more sensitive to factors related to motivation and yet others may be influenced by an interaction of demands and motivation, including individual differences in auditory abilities and motivation. The 3D plot can serve to illustrate interindividual differences and intraindividual differences across conditions, as well as fluctuations in effort associated with variations in demands and motivation during the course of engaging in a complex task. For example, superimposed on the 3D plot is an illustration of how the effort expended by a person who is being studied might change over the time course of an activity as a function of both demand (e.g., task difficulty) and motivation (e.g., evaluation of success importance). For the case of a person attending a cocktail party, the following changes in effort due to changes in demands and motivation are plotted in the segments shown in the 3D plot: segment T0 to T1 shows little change in effort while demands are held constant at a low level, although there is increasing motivation as the person's engagement in the task ramps up (this might happen if there is relatively little background noise but the topic of conversation becomes increasingly interesting); segments T1 to T2 to T3 show an increase in effort while motivation is held more or less constantly high but demands increase gradually (this might happen if the conversation continues to be highly interesting but the level of background noise increases as more people arrive at the party); segment T3 to T4 shows a sharp decrease in effort while demands remain more or less constantly high but motivation decreases rapidly (this might happen if the level of background noise remains steady but the highly interesting story finishes and the conversation becomes uninteresting). This final scenario is consistent with the development of fatigue. Specifically, our hypothetical individual could be viewed as initially being motivated to complete the demanding task and thus being willing to expend substantial effort to achieve that goal. However, over time, the effort-reward ratio becomes unacceptable, leading to the subjective experience of fatigue, a concomitant decrease in motivation to continue expending effort, and finally, a resultant drop in the effort expended on the task. At an extreme, it would be possible to use Figure 2 to illustrate a person "quitting" on one task and reallocating effort to another task. By explicitly portraying the possibility of independent and interactive contributions of various factors affecting demand and/or motivation, we hope that our FUEL will facilitate advances in our thinking about and our understanding of effortful listening. It may also guide research to discover what the underlying mechanisms are and how the connections between these mechanisms operate. Existing results may need to be reinterpreted in the light of our FUEL, and our FUEL may help in reconciling apparent discrepancies between studies. Our FUEL may also inspire the design and interpretation of future research and provide a useful support for counseling and the planning and evaluation of interventions to reduce effort by either altering factors pertaining to the demand and/or the motivation dimension.

METHODS AND MEASURES

The second of the three main goals of the Workshop was to consider the methods, techniques, and measures that have been used to study effortful listening. A very useful contribution of the white paper of the BSA group was the compilation of a list of purported measures of listening effort and, to a more limited extent, measures of fatigue. The measures they identified were organized into three categories according to the technique for administering the measures: behavioral measures, physiological measures, or self-report measures (see also Rudner et al. 2012). We considered the measures reviewed by the BSA group and also additional measures based on work covered in the articles of our workshop participants. It seems likely that, rather than inventing new measures, the future development of measures of listening effort and guidelines for their use in research or practice will involve clarifying which measure or combination of measures is most appropriate to use and for what purposes. Compared with measures of listening effort, however, it is less clear how measures of fatigue specific to listening could be developed.

Our consensus was that many measures could provide a measurable index of the construct of listening effort. However, in light of our proposed FUEL, a new way to categorize candidate measures is according to whether they have been used to primarily examine changes in listening effort as a function of variation in demands and/or as a function of motivation. It is potentially very useful to identify the measures that are most responsive to variations in the demand dimension versus the motivation dimension or the measures tap both dimensions. For example, behavioral cognitive measures (e.g., working memory span) have been used primarily to study the effects of manipulations in the demand dimension rather than the motivation dimension. Among physiological measures, some [e.g., preejection period (PEP)] have been used primarily to study the effects of manipulations in the motivation dimension rather than the demand dimension. Still other measures (e.g., pupil dilation) may capture changes in effort due to both demands and motivation. Furthermore, some self-report measures are based more on demands (e.g., the emphasis is on perception of task difficulty), while others are based more on motivation (e.g., the emphasis on success importance). With respect to our FUEL, some measures of effort might be mapped to responses (i.e., attention-related responses) that could depend on manipulations of demands (e.g., input-related demands) or motivation (e.g., the evaluation of demands in relation to performance). In addition, other measures may serve to assess inter- and intraindividual differences in available capacity (e.g., working memory), how it fluctuates with the amount of arousal (e.g., stress-related hormones), or how the allocation policy operates (e.g., executive functions).

In addition to delineating measures with respect to their mapping to the FUEL, our consensus was that future basic research will need to investigate the mechanisms underlying listening effort and that research to advance practice will need to consider the clinical purposes for investigating listening effort. We agreed that there were three broad purposes for using measures of listening effort in practice: (1) for assessment and the determination of candidacy for particular treatments or technologies; (2) to evaluate and compare outcomes of treatments or technologies; and (3) to screen for clinically significant cognitive impairment or dementia. Once one or more appropriate measures are identified and more is understood about how the measures relate to underlying mechanisms, work will still need to be done to validate and norm tests and to specify standard procedures for administering them and for interpreting them clinically.

Methods

The choice of the specific dependent measure of listening effort will depend on the purpose for which it is used. In the design of experiments, choices will also need to be made about how to implement variants of test protocols and conditions depending on the population, the intervention, and which comparisons will be made using the chosen dependent measure. These sorts of decisions may also apply to the implementation of chosen measures of listening effort in clinical protocols, following the Population, Intervention or interest, Comparison group or intervention, Outcome method advocated for evidence-based medicine (Sackett et al. 2000).

Population and Comparisons of Groups • In terms of population, the suitability of and norms for tests of listening effort and fatigue will need to be determined for different populations (e.g., children, healthy older adults, and adults with comorbidities such other sensory or cognitive impairments). Within groups, tests to detect interindividual differences may be of interest.

Between-group comparisons may be of interest: younger versus older adults; people with versus without hearing loss; people with less versus more hearing loss; people with sensory versus neural hearing loss; people who are healthy versus those who are depressed; cognitively normal versus cognitively impaired; native versus nonnative speakers, and so on. Longitudinal studies may also be valuable, especially given the ample evidence of plasticity and brain development in children and brain reorganization in aging adults. For example, brain imaging studies suggest that older adults may compensate for sensory or motor declines by activating more widespread brain regions (for reviews, see Li et al. 2005; Reuter-Lorenz & Cappell 2008; Park & Reuter-Lorenz 2009; Grady 2012); however, the potential for cognitive compensation for sensory or motor declines may be limited by cognitive declines (Seidler et al. 2010). Ideally, these changes should be followed longitudinally because age-related changes in cognition may be overestimated in cross-sectional studies in which cohort effects are not controlled (Rönnlund et al. 2005).

Interventions and Comparisons of Interventions • With reference to the FUEL, additional within-subject comparisons that warrant further research should explore how listening effort is affected by interventions (e.g., communication training or the use of hearing technologies) or experimental conditions that manipulate the demand dimension and/or the motivation dimension. For example, manipulations in the demand dimension could include comparisons such as steady state versus two-talker competition; normal versus speeded rate of speech; less versus more difference between the fundamental frequencies of the target and competing talker voices (male versus male or male versus female); with versus without spatial separation in multitalker scenes; with versus without visual cues; single-task versus dual-task conditions; with versus without supportive semantic or situational context; with familiar versus unfamiliar music; neutral versus emotional speech; with versus without hearing aid; with hearing aid A versus hearing aid B; and pre- vs. post musical training. Manipulations in the motivation dimension could include comparisons such as low versus high success importance conditions; conditions predisposing low versus high fatigue; conditions with versus without stereotype threat; before versus after self-efficacy training; pre- vs. post intervention to promote social support by a significant other of a person who is hard of hearing; pre- vs. post group interventions to develop strategies for goal pursuit/avoidance decisions; pre- vs. post intervention to optimize the pleasure of listening. Note that, for factors in the demand or motivation dimensions that affect listening effort, some manipulations may explore adverse affects that increase listening effort, while others may explore factors that increase listening ease or decrease listening effort. Ultimately, the factors that are modifiable in the direction of reducing listening effort (or even increasing listening pleasure) may foster new insights into existing successful interventions and/or the development of new interventions.

Outcomes • Kahneman (1973, pp. 185) comments that, "the observation of a close correspondence between behavioral and physiological measures provides strong support for an effort theory." He goes on to say (pp. 188) that "The methodological moral is clear: effort or load should always be measured by at least two independent methods, so chosen that they are unlikely to cause structural interference in the same way…. either of these [behavioral] methods could be used in conjunction with physiological measures of effort and arousal….[or] a combination of a behavioral method with measurements of evoked cortical responses." Our consensus was that research should be conducted to examine how well different measures of listening effort are correlated with each other and whether or not it would be advantageous to combine tests. Such research could influence clinical protocols insofar the evidence would support recommendations to the use of a single test or a battery of tests. Below is a list and description of candidate measures that have been and will likely continue to be used in research on listening effort. (Note that this list overlaps with but is not identical to the list published by the BSA group.) The general categories of the measures listed are cognitive-behavioral, physiological, and self-report measures.

Cognitive-Behavioral Measures

Relevant cognitive domains that could be measured using behavioral tests to gauge listening effort include those that index working memory, attention, or speed of processing. These three domains are interrelated. Working memory capacity is limited and can be allocated to processing and storing information during the performance of complex activities such as language comprehension or listening while multitasking. More generally, attention is involved in the allocation of capacity to activities, including the selection and maintenance of information during the performance of one activity (selective attention) or multiple activities (divided attention). Furthermore, it is assumed that the speed of processing slows with increases in the amount of capacity demanded by a task. At a limit, if the available capacity is exceeded, then either processing must slow or else errors occur. Note that traditional audiologic measures of word recognition accuracy may indicate that capacity has been exceeded. In contrast, the appeal of measures of effort is that they could be used to assess how much capacity is allocated to listening as demands increase but before the limits of available capacity are exceeded (see Lunner et al 2016, this issue, pp. 145S–154S).

Working Memory • Tests of working memory based on tasks involving both the processing and the storage of information (e.g., the reading and listening spans in their several versions derived from Daneman & Carpenter 1980; see also Wingfield 2016, this issue, pp. 35S–43S) are more correlated to language comprehension than are other memory tests (e.g., digit span) based on tasks that involve only the storage of information (Daneman & Merikle 1996). In typical working memory span tests, the amount of capacity allocated to processing during a language processing task (i.e., listening or reading effort) is inferred by measuring the number of items that can be recalled from sets of varying size. Given the assumption that capacity if limited, if more capacity is allocated to listening (or reading), then less spare capacity will remain available for storing information. The listening (or reading) span is the maximum set size where the listener recalls all items in the set. Larger listening spans indicate that there was more spare capacity and that less capacity was used for processing information during listening (or reading). By manipulating input-related demands (e.g., the amount or type of background noise) and measuring listening span, it is possible to examine the effects of the manipulation on the allocation of capacity (e.g., Pichora-Fuller et al. 1995). Audiology researchers have used reading or listening span tests in experiments concerning speech-in-noise performance (for a review, see Besser et al. 2013). However, only recently has research begun to standardize a test of working memory span (the Word Auditory Recognition and Recall Measure; Smith, Pichora-Fuller, Wilson et al, in press) for clinical use by audiologists. Another test of working memory that has been used in research on listening is the N-back memory measure that manipulates working memory load (e.g., Rudner et al. 2015; Sommers & Phelps 2016, this issue, pp. 62S–68S). Other tests of listening working memory discussed at the workshop include the Sentence-final Word Identification and Recall test (Lunner et al 2016, this issue, pp. 145S–154S), the Cognitive Spare Capacity test and the Auditory Interference Span test (Rudner 2016, this issue, pp. 69S–76S), which have been developed specifically to measure spare capacity using Swedish speech materials. Spare capacity is important because it may provide an indication of how much information can be encoded into long-term memory and consolidated as knowledge in the process of learning.

Attention • As in Kahneman's capacity model, in the FUEL, capacity can be allocated to one or more activities according to the allocation policy. Given that capacity is limited, the assumption is that as more capacity is allocated to one activity, less capacity will remain for another activity. The ability to divide attention between activities has most often been measured using the dual-task paradigm. Two tasks (a primary and a secondary one) are performed alone or simultaneously. Reduced performance on the secondary task when it is performed in the dual-task condition compared with when it is performed in a single-task condition is used to index the cost of dual-tasking or how much capacity is diverted from the secondary task and allocated to the primary task (see Edwards 2016, this issue, pp. 85S–91S). Insofar as dual-task cost is an index of how much capacity is allocated, it could be used to make inferences about listening effort. Note that the listening working memory span test can be considered as a special case of a dual-task test, with processing information during listening being the primary task and recall being the secondary task.

Speed of Processing • It is widely accepted in cognitive psychology that the amount of time spent to complete a task varies with the amount of capacity allocated to it. In general, processing speed is the fastest rate at which a cognitive operation can be performed with reasonable accuracy (Phillips 2016, this issue, pp. 44S–51S). This index of cognitive capacity allocation is used to gauge pervasive effects (Kail & Salthouse 1994), ranging from sensory to response stages of information processing (Kramer & Madden 2008). It follows a U-shaped trajectory over the lifespan, with differences in processing speed between younger and older adults being among the most widely replicated effects in the domain of cognitive aging (Salthouse 1996). Processing speed is measured as time to perform a given task (e.g., digit-symbol transcription or simple versus choice reaction time). It is not a "process pure" measure. Thus, it is advisable to use multiple measures of processing speed to allow findings to converge on a common underlying construct

(Salthouse & Madden 2008). Reaction time is the most common behavioral measure of speed of processing. In the context of listening effort, this index might include measuring reaction time in the performance of a nonauditory task (e.g., simple versus choice reaction time to simple visual stimuli) and an auditory task, to examine domain-general variance associated with the underlying processing speed construct and domain-specific variance associated with auditory processing speed (Deary et al. 1989; Deary 1994; see Phillips 2016, this issue, pp. 44S–51S for a fuller discussion). When the accuracy of performance is at or near ceiling, hearing researchers have used reaction time measures to evaluate individual differences in speech-in-noise listening (e.g., Hällgren et al. 2001) and the effects of acoustic distortions and semantic context on listening (Goy et al. 2013).

Physiological Measures

Physiological measures that could be useful for measuring listening effort fall into two main categories: measures of brain activity and measures of the autonomic nervous system. The main techniques for measuring neural brain activity that may be useful for indexing listening effort are magnetic encephalography (MEG), evoked-response potentials (ERPs), alpha power in electroencephalography (EEG), and functional magnetic resonance imaging (fMRI). In general, these techniques vary in the quality of information they yield regarding the timing and region-specific localization of brain activity, with ERP yielding the most precise timing information and fMRI yielding the most precise localization information. Measures of the autonomic nervous system may tap sympathetic or parasympathetic responses. In general, the "fight-or-flight" response of the sympathetic nervous system prepares the body for high-energy activity, whereas the parasympathetic nervous system has the complementary effect of relaxing the body and inhibiting or slowing many high-energy functions. Autonomic responses can be measured using pupil, cardiac, skin conductance, or hormonal responses. Some studies have also combined these techniques to investigate the associations among them.

MEG and ERP • MEG and ERP measurements have been used to study time-locked neural activity evoked by the presentation of and the response to stimuli (see Trembley & Backer 2016, this issue, pp. 155S–162S). For example, the amplitude of the time-locked auditory evoked P3a has been shown to be sensitive to the increased attentional demands of a task and the increased effort of listeners (Combs & Polich 2006; Bertoli & Bodmer 2014, 2016). The P3a is a positive-oriented scalp-recorded potential that has a maximum peak amplitude over frontal/central electrode sites with a peak latency falling in the range of 250 to 280 msec. It is associated with brain activity related to attention (especially orienting and involuntary shifts to changes in the environment) and the processing of stimulus novelty (Polich 2003). When the difficulty of speech-in-noise tests increases [e.g., signal to noise ratio (SNR) decreases], the amplitude of the novelty P3 and late positive potential changes; for this reason, ERPs such as these are considered to provide an indirect, physiological measure of listening effort; however, other explanations could also be given (see Trembley & Backer 2016, this issue, pp. 155S–162S).

Alpha Power in EEG • Changes in oscillatory power in EEG, including changes in alpha, theta, and other responses have been interpreted as reflecting increased demands on the storage and inhibition of information. For example, enhanced alpha oscillations (8–13 Hz of the continuous EEG signal) are documented as neural substrates of increased cognitive effort, in line with a functional, inhibitory role of alpha in controlling or gating local circuits of neural activity (e.g., Weisz et al. 2011). Recent research has shown that acoustic degradation (vocoding) of the signal increases alpha oscillations during listening, suggesting that enhanced alpha power is not only modulated by changing domain-general requirements such as the number of stored items, but that challenges arising from mild-to-severe sensory degradation also affect this system. Both manipulations cause an enhancement of oscillatory power in the same time–frequency range (Obleser et al. 2012). Notably, a recent study on alpha power modulation using a working memory paradigm in older hearing-impaired listeners showed that the degree of hearing loss predicted alpha power enhancement (Petersen et al. 2015).

Functional Magnetic Resonance Imaging • fMRI uses blood-oxygen-level-dependent contrast imaging to provide an estimate of brain activity based on the hemodynamic response to increased neuronal demand for oxygenated blood during a task. Notably, frontal brain regions in younger and older adults demonstrate an elevated hemodynamic response when listening tasks are challenging (Vaden et al. 2013, 2015). One interpretation of these kinds of blood-oxygen-level-dependent results related to task demands is that the elevated activity, particularly in the cingulate cortex, reflects a decision-making process about the expected value of working to optimize performance given the potential value realized from the task.

Pupil Responses • For many years, the pupil diameter has been considered to be an index of cognitive processing load (Kahneman 1973; Kramer et al 2016, this issue, pp. 126S–135S). There is ample evidence showing that the pupil diameter is sensitive to momentary, task-evoked load, and effort during mental tasks. However, different parameters in the pupillary response index different concepts or mechanisms. For example, peak pupil dilation indexes momentary load, whereas the resting pupil diameter before and after the presentation of the stimulus indexes an individual's state of engagement. Pupil constriction, as evoked by light (pupil light reflex), indexes parasympathetic activity. Thus, the pupil response always combines the activity of both the sympathetic and the parasympathetic nervous systems. Pupil dilation has been correlated to changes in the acoustics of stimuli and to subjective loudness (Liao et al. 2015). With respect to motivation, a recent study in monkeys found that the firing rate of noradrenergic coeruleus neurons in the brain increased and was correlated with both pupil dilation and effort related to the energization of behavior (Varazzani et al. 2015). It is unknown how pupil responses such as the momentary peak pupil dilation relate to fatigue in the longer term or to stress as indexed by cortisol or other biomarkers of stress, but researchers began to explore these associations (e.g. Kramer et al. 2016, this issue, 126S–135S). Research on cognitive processing load during listening using pupillometry has shown that the pupil response during listening is sensitive to speech intelligibility (Zekveld et al. 2010), type of background noise (Koelewijn et al. 2012), syntactic complexity (Piquado et al. 2010), auditory stimulus characteristics (Kramer et al. 2013), degraded spectral resolution (Winn et al. 2015), cognitive abilities (Zekveld et al. 2011), and divided (versus focused) attention (Koelewijn et al. 2014).

Cardiac Responses • Two cardiac measures that may be related to listening effort are heart-rate variability (HRV) and the PEP.

HRV measures quantify the amount of variation in heart rate over time. HRV can be analyzed in both the time (e.g., standard deviations of interbeat intervals) and the frequency domains (e.g., spectral analysis of variations in interbeat intervals). Most HRV metrics reflect activity from both the sympathetic and the parasympathetic nervous systems; however, two measures, square root of the mean squared difference between normal beats and high-frequency HRV), reflect primarily parasympathetic activity. As reviewed by Mackersie and Calderon-Moultrie (2016, this issue, pp. 118S–125S), a reduction in HRV with increased listening task demand has been observed for several HRV measures, and thus may be useful as an index of listening effort.

The PEP refers to the time interval between the beginning of the excitation of the left heart ventricle and the opening of the aortic valve. It is a direct indicator of myocardial contraction force—the stronger the heart contracts, the shorter is the PEP. Given that myocardial contraction force is mainly determined by sympathetic activity, changes in PEP reflect changes in myocardial sympathetic activity. Researchers working on motivational intensity theory (e.g., Brehm & Self 1989; Wright 1996) have used this relationship between PEP and sympathetic activity to test the effort-related predictions (see Richter 2016, this issue, pp. 111S–117S). The use of PEP in research on listening effort could enable researchers to assess changes in myocardial sympathetic activity associated with listening effort. In combination with the assessment of high-frequency HRV as an indicator of parasympathetic activity, researchers may be able to examine the autonomic nervous system response that characterizes effortful listening.

Skin Conductance Responses • Skin conductance measures quantify the electrical activity on the skin surface. This activity is mediated by the sympathetic nervous system. Skin conductance measures have been used to infer automatic attention (orienting), effort, motivation, and emotional reactivity (Kahneman 1973; Andreassi 2007; Boucsein 2012). An increase in skin conductance with increasing listening task demands has also been observed for some speech repetition tasks, suggesting a potential role in the evaluation of listening effort (see Mackersie & Calderon-Moultrie 2016, this issue, pp. 118S–125S).

Hormonal Responses • Endocrine biomarkers can be used to index the activity of the autonomic nervous system. Several stress hormones are involved in the regulation of the changes that occur in the body in response to stress. In particular, reactions to stress are associated with enhanced secretion of a number of hormones, including but not limited to, cortisol, chromogranin A, and α-amylase. Only a few studies have measured hormonal responses in studies of hearing loss; for example, one study reported preliminary evidence that the effects of noise on the performance of memory and attention tasks, subjective fatigue, and stress measured with cortisol and catecholamines differed between participants who had normal or impaired hearing (Jahncke & Halin 2012). As reviewed by Kramer et al. (2016, this issue, pp. 126S–135S), the relationship between biomarkers of stress and chronic stress resulting from hearing impairment or momentary stress evoked by speech testing is still controversial.

Self-Reported Listening Effort, Fatigue, or Stress

Certainly, people seeking help for hearing problems often provide spontaneous descriptions of their experiences of effortful listening or fatigue. Some researchers and clinicians have attempted to use self-report measures or subjective ratings to assess listeners' self-perceived distress, effort, or fatigue. Visual analog scales (VASs) are often used to assess the self-reported momentary allocation of cognitive capacity to meet particular input-related demands of listening, either during or after a set of trials in the condition(s) of interest; for example, the listener may be asked to indicate on a VAS from 1 to 10 how effortful it was to listen to and repeat words in different SNR conditions. VASs may also be used to assess a listener's motivation to complete a task (see Kramer et al 2016, this issue, pp. 126S–135S). Alternatively, single items addressing listening effort may be extracted from existing questionnaires, such as the Speech Spatial and Qualities of Hearing Scale (Gatehouse & Noble 2004; see also McGarrigle et al. 2014). Notably, perceived effort during task performance may be an indicator of listening effort, but such self-report measures may also be somewhat generic in nature and tap into some sort of more general chronic stress such as need for recovery (Nachtegaal et al. 2009) or fatigue (see Hornsby et al 2016, this issue, pp. 136S–144S).

One example of how self-report measures could be aligned with FUEL is a promising new self-report approach to determine a listener's lowest acceptable performance level (Boothroyd & Schauer 2015), thereby gauging when a listener is likely to give up listening. To measure the lowest acceptable performance level, listeners were given a description of a common hypothetical scenario (conversing on an interesting topic with friends in a restaurant) in various SNR conditions corresponding to recently experienced speech-in-noise test conditions in which word recognition accuracy had been measured. For the hypothetical scenario in each SNR condition, listeners estimated their expected performance in terms of percent correct word recognition and then they indicated how long they would be *able* sustain attention and how long they would be *willing* to sustain attention to listening in the scenario. Listeners also rated how loud, annoying, and distracting the noise was and how much it interfered with speech understanding (following Mackersie et al. 2014; Lane & Mackersie 2015). Interestingly, using these self-report questions, it was possible to categorize listeners into two groups according to motivational factors, one group being more noise-focused and the other being more speech-focused. Importantly, although the two groups performed similarly on the listening test, they demonstrated different tendencies to quit listening with increasing input-related SNR demands, presumably because they differed in their motivation to listen in demanding situations. The noise-focused group was motivated to avoid noise, whereas the speech-focused group was motivated to listen to speech. Such a self-report measure could enable clinicians to consider input-related demands, as well as an individuals' motivational focus in relation to their likelihood of sustaining the allocation of capacity (i.e., effort).

KNOWLEDGE TRANSLATION

Concerning the third main area of the workshop, our consensus was that there is an imperative to translate knowledge about effortful listening into practice because it is a frequently reported and concerning issue for people who are hard of hearing and our current interventions do not adequately address it. Importantly, the need to address the issue of effortful listening compels us to draw on knowledge about auditory and cognitive processing and to augment it with knowledge about motivation and arousal so that we can better assess and ameliorate everyday listening experiences and functioning. Ultimately, such knowledge translation is necessary if we want to prevent avoiding or quitting as a short-term coping strategy and social withdrawal as a long-term health-compromising consequence of listening being too effortful to be sustained.

There is sufficient converging scientific evidence showing that the deployment of cognitive resources can be crucial for listening, especially when demands increase in challenging listening situations. There have been important advances in research, and numerous behavioral, physiological, and self-report measures have been used in experiments. In addition, the articles in this special issue provide many examples of research conducted with participants recruited from clinical populations and research conducted to evaluate the effects of different technologies on listening effort. Research has begun on fatigue in children and adults with hearing loss. Nevertheless, more knowledge is needed concerning the relationship between effortful listening and fatigue. In particular, there could be important clinical implications as new knowledge is discovered concerning the short- and long-term effects of effortful listening on fatigue and possible changes in the functioning of the autonomic nervous system due to chronic listening effort or fatigue. As of now, however, there are still no standardized measures of listening effort or fatigue that are ready for use in routine clinical practice.

Gathering evidence to show the relevance of measures of listening effort for practice and completing research to standardize tests, however, will not be sufficient to guarantee the adoption of measures of listening effort and fatigue in practice. This will only happen if the test protocols used in research can be modified to be feasible for audiologists to conduct within the time-constraints of busy clinics and using methods that are suited to a general population or special populations. Furthermore, for knowledge translation to succeed, audiologists will need (continuing) education to develop new competencies and become comfortable in administering and interpreting tests of listening effort. They will also need to develop expertise in using the results of such tests to inform the planning and evaluation of interventions, including matters related to hearing aid selection, fitting, acclimatization, adherence, and outcomes.

Questions regarding the appropriateness of cognitive screening for dementia by audiologists also call for the translation of knowledge about cognition into practice, but this type of cognitive screening testing differs in a number of ways from measuring listening effort. There is a solid literature demonstrating deficits in cognitive processes, including memory and language, in older adults who have dementia. Clearly, compared with listeners with normal cognition, those who have cognitive impairments will have even more difficulty allocating capacity to specific listening activities, especially in challenging situations. It may not be reasonable to test this population using measures of listening effort that are appropriate for people who have normal cognition. However, for numerous additional reasons, one being that people who are hard of hearing are at greater risk of developing dementia than peers with normal or near-normal hearing, dementia is a comorbidity that needs to be considered in planning rehabilitation for hearing loss, at least by audiologists working with older adults (Pichora-Fuller et al. 2013). There are widely used standardized screening tests for dementia, but performance on these tests can be negatively affected by sensory impairments, and more research is needed to adapt test protocols for people who have sensory impairments (Dupuis et al. 2015; Phillips 2016, this issue, pp. 44S–51S). Again, for successful adoption of these tests in practice, audiologists will need (continuing) education so that they develop new competencies and become comfortable in administering and interpreting cognitive screening tests. Even if audiologists have access to the results of cognitive tests conducted by neuropsychologists, geriatricians, or family physicians, and do not administer such tests themselves, they will still need to develop expertise in using the results of such tests to inform their practice with older adults, especially given the aging of the population.

PRIORITIES

There are many potential ways in which a better understanding of effortful listening could revolutionize practice. However, we are still in the early stages of exploring how to combine and adapt elements of existing theories and models to facilitate a better understanding of effortful listening and the mechanisms underpinning it. We hope that our proposed FUEL can be used to guide future research and to expedite the translation of existing and new scientific knowledge about effortful listening into practical applications that could be implemented in audiology clinics and hearing technology industries. Below is a summary of key priorities for research and practice.

Priorities for Research

A large number of research priorities were identified at the workshop. These are organized below roughly according to the Population, Intervention or interest, Comparison intervention or group, Outcome method advocated for evidence-based medicine (Sackett et al. 2000).

Populations and Comparisons of Groups • Future research on listening effort and fatigue may apply to the general population, including people with normal hearing or with specific degrees or types of hearing loss; however, a lifespan perspective will be needed to discover if and how effortful listening changes as the auditory system develops in children and adolescents or declines in adults. Studies will need to use longitudinal designs, rather than only cross-sectional designs, to determine the short- and long-term associations between listening effort and adjustment to hearing loss. Over time, how do changes in hearing abilities alter the effects of input-related demands and motivation on listening effort? Conversely, over time, how does effortful listening or fatigue affect everyday functioning in terms of participation in social activities, stress, and coping associated with hearing loss or readiness to seek help or take action to manage hearing problems? Is effortful listening associated with psychological, social, or health factors?

Interests—Mechanisms Underpinning Listening Effort and Fatigue • To continue to develop the FUEL, research will be needed to map out the functions underlying the demands and motivation dimensions illustrated in Figure 2. What can patterns of brain activation in response to manipulations of input-related demands and/or motivation (arousal, success importance or adaptive control) reveal about the mechanisms underpinning listening effort or fatigue? Brain imaging, electrophysiological, and neurophysiological (e.g., neurotransmitters) studies will be needed to elucidate the cortical regions and processes involved in effortful listening, how they vary according to demands and motivation, and how they may change over time. Research could also explore and develop applications of Motivational Intensity

Theory to particular challenging auditory tasks. Research will need to consider what confounding factors (e.g., cognitive reserve, personality) should be controlled or factored into an individual differences approach to the study of listening effort.

Interventions—Modifiable Factors • The FUEL should be used for research to identify potential modifiable moderators of listening effort in terms of demands and motivation with the aim of using these research findings to guide the design of interventions that could reduce listening effort. New interventions might be based on research showing how the allocation policy can be altered by training or counseling. New approaches to rehabilitation might be structured based on research regarding the relative importance of automatic and intentional attention compared with input-related demands on capacity, including demands related to source (e.g., accent or emotion of the talker), transmission (e.g., background noise or device), or listener (e.g., hearing loss) factors. New motivational interventions might exploit research on the use of behavioral and neuroeconomics approaches to provide quantitative metrics for explaining when, why, and how much people experience effort and which factors could potentially be modified? A patient-centered approach could incorporate research findings demonstrating the potential for modifying motivation by using strategies to promote task (dis)engagement or boost self-efficacy or listening pleasure. Similarly, new interventions could be developed in response to findings showing that the expected value (success importance) of listening affects the perception or onset of fatigue.

Comparisons of Short Versus Long-term Effects of Treated Versus Untreated Listening Effort • Research is needed to determine whether transient or short-term listening effort and/or fatigue can progress to become chronic debilitating conditions (stress, cognitive impairment, fatigue) and whether interventions could counteract such deleterious long-term effects.

Outcome Measures • There are a large number of potential measures of listening effort and fatigue, but few have been sufficiently operationalized and none have been standardized for clinical use by audiologists. The FUEL could be used in research to determine which of the potential measures are the best, either alone or in combination, for gauging listening effort for different purposes and in different populations. Research to assess the strength of the correlations among measures will be needed to guide decisions about the possible advantages of using a test battery. The ecological validity of potential measures should also be studied to determine how well they predict the everyday experiences of listeners in realistic communication situations, including their likelihood of quitting listening tasks in specific conditions such as conversational interactions. Research using ecological monitoring methods and mobile technology in the real world could be used to validate laboratory-based or clinic-based measures of effortful listening. Research may also clarify if there is a cognitive or listening analog of a physical fatigue measure.

Priorities for Clinical Practice

Many of the priorities for research should lead to the development of new clinical practices. Priorities for practice involve both deepening our understanding regarding what underlies successful aspects of existing practice and developing new practices.

Development of Clinically Feasible and Relevant Measures • Many potential measures of listening effort have been used in the laboratory, but none have been adapted for clinical use. As described in the section on Knowledge Translation, research and education will be needed before viable measures of listening effort could be endorsed for use in the clinic. Research will be needed to determine test properties and the sensitivity and specificity of clinically feasible versions of tests to assess individuals and the outcomes of interventions. An important prerequisite for changing clinical practice will be to establish the purposes for and advantages of using such measures.

Guidelines for Use of Measures in Assessing Candidacy for Interventions • Guidelines will need to be developed concerning the appropriate use of new measures of listening effort. For example, some guidelines might cover how audiologists could use these measures to determine which device features or training regiments to recommend or to predict who would benefit most, report more problems listening, or be more likely to quit listening in what sorts of situations. These measures might influence counseling individuals about appraising success importance, setting goals for managing how listening effort is spent, or how to derive more pleasure from listening or minimize input-related demands (e.g., by selection/modification of communication environments to reduce adversity). Such counseling about listening effort could complement considerations of other emerging topics in rehabilitative assessment such as factors that predispose help-seeking, readiness to take action to manage hearing problems, the benefits of improving self-efficacy, the advantages of social support, and ways to overcome stigma or even stress and risk of dementia (Pichora-Fuller 2016, this issue, pp. 92S–100S). Guidelines would also be needed regarding the appropriate use of cognitive screening for clinically significant cognitive impairment or dementia in rehabilitative audiology, including during hearing aid fitting or training for the person who is hard of hearing or their significant other or caregiver.

New Interventions • If it becomes feasible to measure listening effort in the clinic, existing interventions could be reframed or new interventions developed to reduce listening effort or fatigue (and/or increase ease or pleasure) and to train individuals in strategies to control or regulate the allocation of effort. Based on the research described earlier, interventions could be developed to modify the time course over which listening effort or fatigue affects new hearing aid wearers (e.g., they might be trained to increase endurance, immunizing them from abandoning device use) or to sustain social participation in experienced users and prevent social withdrawal or reduce the risk of dementia.

Evaluating Outcomes of Interventions • Of course, measures of listening effort will need to be validated for use in evaluating the effectiveness of interventions. New outcome measures to evaluate change in listening effort would be extremely useful for evaluating the effectiveness of existing interventions (e.g., do hearing aids reduce/increase effort), to evaluate the comparative effects of different treatments or treatment combinations, and to determine if or how the effects of treatments depend on individual differences related to listening effort.

Other Practice-Related Issues • The development of measures of listening effort suitable for use by audiologists will raise other practice-related issues, including (1) revising the audiology curriculum to educate audiologist about listening effort, how to measure it, and how to use test results, (2) establishing or updating information-sharing about measures of listening effort with interprofessional team members (e.g., psychologists, geriatricians), and (3) delivering public education to increase awareness of new research findings and new rehabilitative options based on new knowledge about listening effort.

CONCLUSION

Our consensus resulted in a proposed FUEL. Our FUEL interprets core concepts from Kahneman's seminal Capacity Model of Attention in relation to studies of listening effort and fatigue. The 3D plot in Figure 2 based on our FUEL provides a way to visualize how the demands and motivation dimensions could independently or interactively modulate effort. Although the scales for the dimensions remain unknown, by visualizing the combined effects of demands and motivation on effort, the 3D figure offers a tool that may inspire a new era of research on listening effort and fatigue that will yield knowledge that can be translated into practice. Areas of practice that could benefit from measures of effort include assessing candidacy for particular technical and/or therapeutic interventions and the evaluation of outcomes. Another important area of practice is cognitive screening for dementia; this area involves the assessment of cognitive ability but is distinct from the measurement of listening effort or fatigue.

ACKNOWLEDGMENTS

We thank the Oticon Foundation for their financial support and staff at the Eriksholm Research Centre for facilitating the workshop. We also acknowledge the excellent feedback we received in the months following the workshop from many colleagues who were not workshop participants. Alexander Francis shared information from the special sessions on *Listening Effort* that he had organized at the 169th Meeting of the Acoustical Society of America held in May 2015. Erv Hafter and Frederick Gallun provided helpful comments about the applicability of a signal-detection approach to listening effort.

The authors have no other conflict of interest to disclose.

This work was supported by a grant from the Oticon Foundation to Graham Naylor and Thomas Lunner for the Fifth Eriksholm Workshop on "Hearing Impairment and Cognitive Energy" held on June 3 to 5, 2015, at the Eriksholm Research Centre, Snekkersten, Denmark.

All authors wrote the present consensus article collaboratively. The first two authors, M. Kathleen Pichora-Fuller and Sophia E. Kramer, were invited to convene the workshop and they contributed equally to the preparation of the consensus article. The other authors, listed alphabetically, were workshop attendees and/or first authors of the set of articles prepared for the workshop and published in this special issue. Brent Edwards and Graham Naylor collaborated to produce the preliminary figure of our FUEL that was revised after the workshop to converge with figures from Kahneman's seminal book *Attention and Effort* (1973). The three-dimensional figure was suggested by Kathy Pichora-Fuller and refined by Larry Humes and Thomas Lunner; MATLAB versions were produced with the assistance of Dorothea Wendt, a postdoctoral fellow in the Department of Electrical Engineering at the Danish Technical Institute and the Eriksholm Research Center.

Address for correspondence: M. Kathleen Pichora-Fuller, Department of Psychology, University of Toronto, 3359 Mississauga Rd, Mississauga, Ontario, Canada L5L 1C6. E-mail: k.pichora.fuller@utoronto.ca

Received December 24, 2015; accepted February 15, 2016.

REFERENCES

Albers, M. W., Gilmore, G. C., Kaye, J., et al. (2015). At the interface of sensory and motor dysfunctions and Alzheimer's disease. *Alzheimers Dement*, *11*, 70–98.

Anderson, S., Parbery-Clark, A., White-Schwoch, T., et al. (2012). Aging affects neural precision of speech encoding. *J Neurosci*, *32*, 14156–14164.

Anderson Gosselin, P., & Gagné, J. P. (2011). Older adults expend more listening effort than young adults recognizing speech in noise. *J Speech Lang Hear Res*, *54*, 944–958.

Andreassi, J. L. (2007). Psychophysiology: Human Behavior and Physiological Response (5th ed.). Mahway, NJ: Lawrence Erlbaum Associates.

Arehart, K. H., Souza, P., Baca, R., et al. (2013). Working memory, age, and hearing loss: Susceptibility to hearing aid distortion. *Ear Hear*, *34*, 251–260.

Arlinger, S., Lunner, T., Lyxell, B., et al. (2009). The emergence of cognitive hearing science. *Scand J Psychol*, *50*, 371–384.

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.

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: A new window to the study of cognitive aging? *Psychol Aging*, *12*, 12–21.

Bandura, A. (1997). Self Efficacy: The Exercise of Control. New York, NY: Freeman.

Bertoli, S., & Bodmer, D. (2014). Novel sounds as a psychophysiological measure of listening effort in older listeners with and without hearing loss. *Clin Neurophysiol*, *125*, 1030–1041.

Bertoli, S., & Bodmer, D. (2016). Effects of age and task difficulty on ERP responses to novel sounds presented during a speech-perception-in-noise test. *Clin Neurophysiol*, *127*, 360–368.

Besser, J., Koelewijn, T., Zekveld, A. A., et al. (2013). How linguistic closure and verbal working memory relate to speech recognition in noise—A review. *Trends Amplif*, *17*, 75–93.

Boothroyd, A., & Schauer, A. (2015 October). Lowest acceptable performance level. *Presented at the Meeting of the International Collegium of Rehabilitative Audiology*, Berkeley, CA.

Borg, E., Bergkvist, C., Olsson, I. S., et al. (2008). Communication as an ecological system. *Int J Audiol*, *47(Suppl 2)*, S131–S138.

Boucsein, W. (2012). *Electrodermal Activity* (2nd ed.). New York, NY: Springer.

Bregman, A. (1990). Auditory Scene Analysis: The Perceptual Organization of Sound. Cambridge, MA: MIT Press.

Brehm, J. W., & Self, E. A. (1989). The intensity of motivation. *Annu Rev Psychol*, *40*, 109–131.

Broadbent, D. E. (1958). Perception and Communication. London: Pergamon Press.

Carpenter, P. A., Miyaki, A., Just, M. A. (1994). Working memory constraints in comprehension: Evidence from individual differences, aphasia, and aging. In M. Gernsbacher (Ed.), Handbook of Psycholinguistics (pp. 1075–1122). San Diego, CA: Academic Press.

Carpenter, P. A., Miyake, A., Just, M. A. (1995). Language comprehension: Sentence and discourse processing. *Annu Rev Psychol*, *46*, 91–120.

CHABA (Committee on Hearing, Bioacoustics and Biomechanics). (1988). Speech understanding and aging. *J Acoust Soc Am*, *83*, 859–895.

Chasteen, A., Pichora-Fuller, M. K., Dupuis, K., et al. (2015). Do negative views of aging influence memory and auditory performance through self-perceived abilities? *Psychol Aging*, *30*, 881–893.

Clinard, C. G., Tremblay, K. L., Krishnan, A. R. (2010). Aging alters the perception and physiological representation of frequency: Evidence from human frequency-following response recordings. *Hear Res*, *264*, 48–55.

Cohen, G. (1987). Speech comprehension in the elderly: The effects of cognitive changes. *Br J Audiol*, *21*, 221–226.

Cohen, S. (2004). Social relationships and health. *Am Psychol*, *59*, 676–684.

Combs, L. A., & Polich, J. (2006). P3a from auditory white noise stimuli. *Clin Neurophysiol*, *117*, 1106–1112.

Craik, F. I. M., Bialystok, E. (2008). Lifespan cognitive development. In F. I. M. Craik & T. Salthouse (Eds), The Handbook of Aging and Cognition, 3rd ed (pp. 557–601). Mahwah, NJ: Lawrence Erlbaum Associates.

Daneman, M., & Carpenter, P. (1980). Individual differences in working memory and reading. *J Verb Learn Verb Beh*, *19*, 450–466.

Danermark, B., Granberg, S., Kramer, S. E., et al. (2013). The creation of a comprehensive and a brief core set for hearing loss using the International Classification of Functioning. *Am J Audiol*, *22*, 323–328.

Daneman, M., & Merikle, P. M. (1996). Working memory and language comprehension: A meta-analysis. *Psychon Bull Rev*, *3*, 422–433.

Davis, A. (2003). Population study of the ability to benefit from amplification and the provision of a hearing aid in 55-74-year-old first-time hearing aid users. *Int J Audiol*, *42(Suppl 2)*, 2S39–2S52.

Deary, I. J. (1994). Intelligence and auditory discrimination: Separating processing speed and fidelity of stimulus representation. *Intelligence*, *18*, 189–213.

Deary, I. J., Caryl, P. G., Egan, V. et al. (1989). Visual and auditory inspection time: Their interrelationship and correlations with IQ in high ability subjects. *Pers Individ Dif*, *10*, 525–533.

Denes, P. B., & Pinson, E. N. (1963). The Speech Chain: The Physics and Biology of Spoken Language. Murray Hill, NJ: Bell Telephone Laboratories.

Dupuis, K., Pichora-Fuller, M. K., Chasteen, A. L., et al. (2015). Effects of hearing and vision impairments on the Montreal Cognitive Assessment. *Neuropsychol Dev Cogn B Aging Neuropsychol Cogn*, *22*, 413–437.

Eckert, M. A., Teubner-Rhodes, S., Vaden, K. (2016). Neuroimaging of adaptive control during speech and language processing. *Ear Hear*, *37*, 101S–110S.

Edwards, B. A. (2016). Model of auditory-cognitive processing and relevance to clinical applicability. *Ear Hear*, *37*, 85S–91S.

Elliot, A. J. (Ed). (2013). Handbook of Approach and Avoidance Motivation. New York, NY: Psychology Press; Taylor & Francis Group LLC.

Erber, N. P. (1988). Communication Therapy for Hearing-Impaired Adults. Abbotsford, Australia: Clavis.

Fitzgibbons, P. J., & Gordon-Salant, S. (2010). Behavioral studies with aging humans: Hearing sensitivity and psychoacoustics. In S. Gordon-Salant, R. D. Frisina, A. Popper, et al. (Eds.), *The Aging Auditory System: Perceptual Characterization and Neural Bases of Presbycusis.* Springer Handbook of Auditory Research (pp. 111–134). Berlin: Springer.

Foo, C., Rudner, M., Rönnberg, J., et al. (2007). Recognition of speech in noise with new hearing instrument compression release settings requires explicit cognitive storage and processing capacity. *J Am Acad Audiol*, *18*, 618–631.

Fraser, S., Gagné, J.-P., Alepins, M., et al. (2011). Evaluating the effort expended to understand speech in noise using a dual-task paradigm: The effects of providing visual speech cues. *J Speech Lang Hear Res*, *53*, 18–33.

Gatehouse, S., Naylor, G., Elberling, C. (2003). Benefits from hearing aids in relation to the interaction between the user and the environment. *Int J Audiol*, *42*, 1S77–1S86.

Gatehouse, S., Naylor, G., Elberling, C. (2006a). Linear and nonlinear hearing aid fittings–1. Patterns of benefit. *Int J Audiol*, *45*, 130–152.

Gatehouse, S., Naylor, G., Elberling, C. (2006b). Linear and nonlinear hearing aid fittings–2. Patterns of candidature. *Int J Audiol*, *45*, 153–171.

Gatehouse, S., & Noble, W. (2004). The Speech, Spatial and Qualities of Hearing Scale (SSQ). *Int J Audiol*, *43*, 85–99.

Gergelyfi, M., Jacob, B., Olivier, E., et al. (2015). Dissociation between mental fatigue and motivational state during prolonged mental activity. *Front Behav Neurosci*, *9*, 176.

Goy, H., Pelletier, M., Coletta, M., et al. (2013). The effects of semantic context and the type and amount of acoustic distortion on lexical decision by younger and older adults. *J Speech Lang Hear Res*, *56*, 1715–1732.

Grady, C. (2012). The cognitive neuroscience of ageing. *Nat Rev Neurosci*, *13*, 491–505.

Hällgren, M., Larsby, B., Lyxell, B., et al. (2001). Evaluation of a cognitive test battery in young and elderly normal-hearing and hearing-impaired persons. *J Am Acad Audiol*, *12*, 357–370.

Handel, S. (1989). Listening: An Introduction to the Perception of Auditory Events. Cambridge, MA: MIT Press.

Hick, C. B., & Tharpe, A. M. (2002). Listening effort and fatigue in school-age children with and without hearing loss. *J Speech Lang Hear Res*, *45*, 573–584.

Hockey, R. (2013). The Psychology of Fatigue: Work, Effort and Control. Cambridge: University Press.

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

Humes, L. E. (2003). Modeling and predicting hearing aid outcome. *Trends Amplif*, *7*, 41–75.

Humes, L. E. (2007). The contributions of audibility and cognitive factors to the benefit provided by amplified speech to older adults. *J Am Acad Audiol*, *18*, 590–603.

Humes, L. E., & Bess, F. H. (2013). Audiology and Communication Disorders: An Overview (2nd ed.). Baltimore, MD: Lippincott, Williams & Wilkins.

Humes, L. E., Busey, T. A., Craig, J., et al. (2013). Are age-related changes in cognitive function driven by age-related changes in sensory processing? *Atten Percept Psychophys*, *75*, 508–524.

Humes, L. E., & Floyd, S. S. (2005). Measures of working memory, sequence learning, and speech recognition in the elderly. *J Speech Lang Hear Res*, *48*, 224–235.

Humes, L. E., Kidd, G. R., Lentz, J. J. (2013). Auditory and cognitive factors underlying individual differences in aided speech-understanding among older adults. *Front Syst Neurosci*, *7*, 55.

Humes, L. E., & Wilson, D. L. (2003). An examination of changes in hearing-aid performance and benefit in the elderly over a 3-year period of hearing-aid use. *J Speech Lang Hear Res*, *46*, 137–145.

Humes, L. E., & Young, L. A. (2016). Sensory-cognitive interactions in older adults. *Ear Hear*, *37*, 52S–61S.

ICF Research Branch. (2013). ICF Core Set for Hearing Loss. Available at: https://www.icf-research-branch.org/icf-core-sets-projects2/other-health-conditions/icf-core-set-for-hearing-loss retrieved May 4, 2016.

Jahncke, H., & Halin, N. (2012). Performance, fatigue and stress in open-plan offices: The effects of noise and restoration on hearing impaired and normal hearing individuals. *Noise Health*, *14*, 260–272.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychol Rev*, *99*, 122–149.

Kahneman, D. (1973). *Attention and Effort*. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Kail, R., & Salthouse, T. A. (1994). Processing speed as a mental capacity. *Acta Psychol (Amst)*, *86*, 199–225.

Kiessling, J., Pichora-Fuller, M. K., Gatehouse, S., et al. (2003). Candidature for and delivery of audiological services: Special needs of older people. *Int J Audiol*, *42*, S92–S101.

Koelewijn, T., Shinn-Cunningham, B. G., Zekveld, A. A., et al. (2014). The pupil response is sensitive to divided attention during speech processing. *Hear Res*, *312*, 114–120.

Koelewijn, T., Zekveld, A. A., Festen, J. M., et al. (2012). Pupil dilation uncovers extra listening effort in the presence of a single-talker masker. *Ear Hear*, *33*, 291–300.

Kramer, A. F., & Madden, D. J. (2008). Attention. In F. I. M. Craik & T. A. Salthouse (Eds.), Handbook of Aging and Cognition (3rd ed., pp. 189–249). New York, NY: Psychology Press.

Kramer, S. E., Lorens, A., Coninx, F., et al. (2013). Processing load during listening: The influence of task characteristic on the pupil response. *J Lang Cogn Process*, *28*, 426–442.

Kramer, S. E., Teunissen, C., 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.

Kuhn, T. (1962). The Structure of Scientific Revolutions. Chicago, IL: University of Chicago Press.

Lane, M., & Mackersie, C. L. (2015 Mar). Sound tolerance domains: Effects of noise type. *Presented at the American Auditory Society*, Scottsdale, AZ.

Lee, D., Seo, H., Jung, M. W. (2012). Neural basis of reinforcement learning and decision making. *Annu Rev Neurosci*, *35*, 287–308.

Lemke, U., & Besser, J. (2016). Cognitive load and listening effort: a working model and its application in old age. *Ear Hear*, *37*, 77S–84S.

Li, K. Z. H., Krampe, R. Th., & Bondar, A. (2005). An ecological approach to studying aging and dual-task performance. In R. W. Engle, G. Sedek, U. von Hecker, et al. (Eds.), *Cognitive Limitations in Aging and Psychopathology* (pp. 190–218). Cambridge: Cambridge University Press.

Liao, H. I., Kidani, S., Yoneya, M., et al. (2015). Correspondences among pupillary dilation response, subjective salience of sounds, and loudness. *Psychon Bull Rev*, *23*, 412–425.

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: A strong connection. *Psychol Aging*, *9*, 339–355.

Lopez-Poveda, E. A. (2014). Why do I hear but not understand? Stochastic undersampling as a model of degraded neural encoding of speech. *Front Neurosci*, *8*, 348.

Lunner, T. (2003). Cognitive function in relation to hearing aid use. *Int J Audiol*, *42 (Suppl 1)*, S49–S58.

Lunner, T., & Sundewall-Thorén, E. (2007). Interactions between cognition, compression, and listening conditions: Effects on speech-in-noise performance in a two-channel hearing aid. *J Am Acad Audiol*, *18*, 604–617.

Lunner, T., Rudner, M., Rosenbom, T., et al. (2016). Using speech recall in hearing aid fitting and outcome evaluation under ecological test conditions. *Ear Hear*, *37*, 145S–154S.

Mackersie, C. L., Baxter, S., Lane, M. (2014 August). Domains of sound-tolerance underlying Acceptable Noise Level. *Presented at the International Hearing Aid Research Conference (IHCON)*, Lake Tahoe, CA.

Mackersie, C. L., & Calderon-Moultrie, N. (2016). Autonomic nervous system reactivity during speech recognition tasks: Heart-rate variability and skin conductance. *Ear Hear*, *37*, 118S–125S.

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

Mattys, S. L., Davis, M. H., Bradlow, A. R., et al. (2012). Speech recognition in adverse conditions: A review. *Lang Cogn Process*, *27*, 953–978.

McAdams, S., & Bigand, E. (1993). Thinking in Sound: The Cognitive Psychology of Human Audition. Oxford, UK: Oxford University Press.

McGarrigle, R., Munro, K. J., Dawes, P., et al. (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*, 433–440.

Nachtegaal, J., Kuik, D. J., Anema, J. R., et al. (2009). Hearing status, need for recovery after work, and psychosocial work characteristics: Results from an internet-based national survey on hearing. *Int J Audiol*, *48*, 684–691.

Neher, T. (2014). Relating hearing loss and executive functions to hearing aid users' preference for, and speech recognition with, different combinations of binaural noise reduction and microphone directionality. *Front Neurosci*, *8*, 391.

Neuhoff, J. G. (Ed.). (2004). *Ecological Psychoacoustics*. New York, NY: Academic Press.

Ng, E. H., Rudner, M., Lunner, T., et al. (2013). Effects of noise and working memory capacity on memory processing of speech for hearing-aid users. *Int J Audiol*, *52*, 433–441.

Ng, E. H., Rudner, M., Lunner, T., et al. (2015). Noise reduction improves memory for target language speech in competing native but not foreign language speech. *Ear Hear*, *36*, 82–91.

Obleser, J., Wöstmann, M., Hellbernd, N., et al. (2012). Adverse listening conditions and memory load drive a common α oscillatory network. *J Neurosci*, *32*, 12376–12383.

Ohlenforst, B., Souza, P. E., MacDonald, E. N. (2016). Exploring the relationship between working memory, compressor speed, and background noise characteristics. *Ear Hear*, *37*, 137–143.

Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain: Aging and neurocognitive scaffolding. *Annu Rev Psychol*, *60*, 173–196.

Petersen, E. B., Wöstmann, M., Obleser, J., et al. (2015). Hearing loss impacts neural alpha oscillations under adverse listening conditions. *Front Psychol*, *6*, 177.

Phillips, N. (2016). The implications of cognitive aging for listening and the FUEL model. *Ear Hear*, *37*, 44S–51S.

Pichora-Fuller, M. K. (2003). Cognitive aging and auditory information processing. *Int J Audiol*, *42(Suppl 2)*, 2S26–2S32.

Pichora-Fuller, M. K. (2006). Perceptual effort and apparent cognitive decline: Implications for audiologic rehabilitation. *Semin Hear*, *27*, 284–293.

Pichora-Fuller, M. K. (2007). Audition and cognition: What audiologists need to know about listening. In C. Palmer, & R. Seewald (Eds.). *Hearing Care for Adults* (pp. 71–85). Stäfa, Switzerland: Phonak.

Pichora-Fuller, M. K. (2010). Using the brain when the ears are challenged helps healthy older listeners compensate and preserve communication function. In L. Hickson (Ed.). *Hearing Care for Adults* (pp. 53–65). Stäfa, Switzerland: Phonak.

Pichora-Fuller, M. K. (2013). Auditory and cognitive processing in audiologic rehabilitation. In J. Spitzer & J. Montano (Eds.), *Adult Audiologic Rehabilitation: Advanced Practices* (2nd ed., pp. 519–536). San Diego, CA: Plural Publishing.

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

Pichora-Fuller, M. K., Dupuis, K., Reed, M., et al. (2013). Helping older people with cognitive decline communicate: Hearing aids as part of a broader rehabilitation approach. *Semin Hearing*, *34*, 307–329.

Pichora-Fuller, M. K., Johnson, C. E., Roodenburg, K. E. J. (1998). The discrepancy between hearing impairment and handicap in the elderly: Balancing transaction and interaction in conversation. *J Applied Comm Res*, *26*, 99–119.

Pichora-Fuller, M. K., Mick, P. T., Reed, M. (2015). Hearing, cognition, and healthy aging: Social and public health implications of the links between age-related declines in hearing and cognition. *Semin Hearing*, *36*, 122–139.

Pichora-Fuller, M. K., Schneider, B. A., Daneman, M. (1995). How young and old adults listen to and remember speech in noise. *J Acoust Soc Am*, *97*, 593–608.

Pichora-Fuller, M. K., & Singh, G. (2006). Effects of age on auditory and cognitive processing: Implications for hearing aid fitting and audiologic rehabilitation. *Trends Amplif*, *10*, 29–59.

Picou, E. M., Ricketts, T. A., Hornsby, B. W. (2011). Visual cues and listening effort: Individual variability. *J Speech Lang Hear Res*, *54*, 1416–1430.

Piquado, T., Isaacowitz, D., Wingfield, A. (2010). Pupillometry as a measure of cognitive effort in younger and older adults. *Psychophysiology*, *47*, 560–569.

Polich, J. (2003). Overview of P3a and P3b. In J. Polich (Ed.), Detection of Change: Event-Related Potential and fMRI Findings (pp. 83–98). Boston, MA: Kluwer Academic Press.

Postle, B. R. (2006). Working memory as an emergent property of the mind and brain. *Neuroscience*, *139*, 23–38.

Rabbitt, P. M. (1968). Channel-capacity, intelligibility and immediate memory. *Q J Exp Psychol*, *20*, 241–248.

Rabbitt, P. M. (1990). Mild hearing loss can cause apparent memory failures which increase with age and reduce with IQ. *Acta Otolaryngol Suppl*, *476*, 167–175; discussion 176.

Reitan, R. M., & Wolfson, D. (2000). Conation: A neglected aspect of neuropsychological functioning. *Arch Clin Neuropsychol*, *15*, 443–453.

Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive aging and the compensation hypothesis. *Curr Dir Psychol Sci*, *17*, 177–182.

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

Robertson, L., Pichora-Fuller, M. K., Jennings, M.-B., et al. (1997). The effect of an aural rehabilitation program on responses to scenarios depicting communication breakdown. *J Speech Lang Pathol Audiol*, *21*, 187–198.

Rönnberg, J., Lunner, T., Zekveld, A. A., et al. (2013). The ease of language understanding (ELU) model: Theoretical, empirical and clinical advances. *Front Syst Neurosci*, *13*, 7–31.

Rönnberg, J., Rudner, M., Foo, C., et al. (2008). Cognition counts: A working memory system for ease of language understanding (ELU). *Int J Audiol*, *47(Suppl 2)*, S99–S105.

Rönnlund, M., Nyberg, L., Bäckman, L., et al. (2005). Stability, growth, and decline in adult life span development of declarative memory: Cross-sectional and longitudinal data from a population-based study. *Psychol Aging*, *20*, 3–18.

Rudner, M. (2016). Cognitive spare capacity as an index of listening effort. *Ear Hear*, *37*, 69S–76S.

Rudner, M., Foo, C., Rönnberg, J., et al. (2009). Cognition and aided speech recognition in noise: Specific role for cognitive factors following nine-week experience with adjusted compression settings in hearing aids. *Scand J Psychol*, *50*, 405–418.

Rudner, M., Foo, C., Sundewall Thorén, E., et al. (2008). Phonological mismatch and explicit cognitive processing in a sample of 102 hearing aid users. *Int J Audiol*, *47*, S163–S170.

Rudner, M., Lunner, T., Behrens, T., et al. (2012). Working memory capacity may influence perceived effort during aided speech recognition in noise. *J Am Acad Audiol*, *23*, 577–589.

Rudner, M., Rönnberg, J., Lunner, T. (2011). Working memory supports listening in noise for persons with hearing impairment. *J Am Acad Audiol*, *22*, 156–167.

Rudner, M., Toscano, E., Holmer, E. (2015). Load and distinctness interact in working memory for lexical manual gestures. *Front Psychol*, *6*, 1147.

Ryan, E. B., Giles, H., Bartolucci, G., et al. (1986). Psycholinguistic and social psychological components of communication by and with the elderly. *Lang Commun*, *6*, 1–24.

Ryan, E. B., Meredith, S. D., MacLean, M. J., et al. (1995). Changing the way we talk with elders: Promoting health using the communication enhancement model. *Int J Aging Hum Dev*, *41*, 89–107.

Sackett, D. L., Straus, S. E., Richardson, W. S., et al. (2000). Evidence-Based Medicine: How to Practice and Teach EBM (2nd ed.). Edinburgh: Churchill Livingstone.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychol Rev*, *103*, 403–428.

Salthouse, T. A., & Madden, D. J. (2008). Information processing speed and aging. In J. DeLuca & J. Kalmar (Eds.), Information Processing Speed in Clinical Populations (pp. 221–241). New York, NY: Psychology Press.

Schneider, B. A., & Pichora-Fuller, M. K. (2000). Implications of perceptual processing for cognitive aging research. In F. I. M. Craik & T. A. Salthouse (Eds.), The Handbook of Aging and Cognition (2nd ed., pp. 155–219). Mahway, NJ: Lawrence Erlbaum Associates.

Schneider, B. A., Pichora-Fuller, M. K., Daneman, M. (2010). The effects of senescent changes in audition and cognition on spoken language comprehension. In S. Gordon-Salant, R. D. Frisina, A. Popper, et al. (Eds.), *The Aging Auditory System: Perceptual Characterization and Neural Bases of Presbycusis. Springer Handbook of Auditory Research* (pp. 167–210). Berlin: Springer.

Seidler, R. D., Bernard, J. A., Burutolu, T. B., et al. (2010). Motor control and aging: Links to age-related brain structural, functional, and biochemical effects. *Neurosci Biobehav Rev*, *34*, 721–733.

Smith, S., Pichora-Fuller, M.K., Wilson, R., et al. (in press). Development of the Word Auditory Recognition and Recall Measure

(WARRM): A working memory test for use in rehabilitative audiology. *Ear Hear*.

Sommers, M. S., & Phelps, D. (2016). The effects of adding visual speech information on measures of perceptual effort in young and older listeners. *Ear Hear*, *37*, 62S–68S.

Souza, P. E., Arehart, K. H., Shen, J., et al. (2015). Working memory and intelligibility of hearing-aid processed speech. *Front Psychol*, *6*, 526.

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

Titchener, E. B. (1908). Lectures on the Elementary Psychology of Feeling and Attention. New York, NY: Macmillan.

Tremblay, K., & Backer, K. (2016). Listening and learning: Implications for the rehabilitation of adults with and without hearing loss. *Ear Hear*, *37*, 155S–162S.

Vaden, K. I. Jr, Kuchinsky, S. E., Ahlstrom, J. B., et al. (2015). Cortical activity predicts which older adults recognize speech in noise and when. *J Neurosci*, *35*, 3929–3937.

Vaden, K. I. Jr, Kuchinsky, S. E., Cute, S. L., et al. (2013). The cingulo-opercular network provides word-recognition benefit. *J Neurosci*, *33*, 18979–18986.

Valente, M., Abrams, H., Benson, D., et al. (2006). Guidelines for the Audiologic Management of Adult Hearing Impairment, Task Force Report for the American Academy of Audiology. Retrieved from http://www.audiologyonline.com/articles/guideline-for-audiologic-management-adult-966. Retrieved on May 4, 2016.

Varazzani, C., San-Galli, A., Gilardeau, S., et al. (2015). Noradrenaline and dopamine neurons in the reward/effort trade-off: A direct electrophysiological comparison in behaving monkeys. *J Neurosci*, *35*, 7866–7877.

Weisz, N., Hartmann, T., Müller, N., et al. (2011). Alpha rhythms in audition: Cognitive and clinical perspectives. *Front Psychol*, *2*, 73.

Wingfield, A. (2016). The evolution of models of working memory and cognitive resources. *Ear Hear*, *37*, 35S–43S.

Wingfield, A., McCoy, S. L., Peelle, J. E., et al. (2006). Effects of adult aging and hearing loss on comprehension of rapid speech varying in syntactic complexity. *J Am Acad Audiol*, *17*, 487–497.

Wingfield, A., & Tun, P. A. (2001). Spoken language comprehension in older adults: Interactions between sensory and cognitive change in normal aging. *Semin Hearing*, *22*, 287–301.

Wingfield, A., Tun, P. A., & McCoy, S. L. (2005). Hearing loss in older adulthood: What it is and how it interacts with cognitive performance. *Curr Dir Psychol Sci*, *14*, 144–148.

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*, e153–e165.

World Health Organization (WHO). (2001). International Classification of Functioning, Disability and Health. Geneva: World Health Organization.

Wright, R. A. (1996). Brehm's theory of motivation as a model of effort and cardiovascular response. In P. M. Gollwitzer & J. A. Bargh (Eds.), The Psychology of Action: Linking Cognition and Motivation to Behavior (pp. 424–453). New York, NY: Guilford.

Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *J Comparative Neurology and Psychology*, *18*, 459–482.

Zekveld, A. A., Kramer, S. E., Festen, J. M. (2010). Pupil response as an indication of effortful listening: The influence of sentence intelligibility. *Ear Hear*, *31*, 480–490.

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*, 498–510.