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Discussion paper

Listening effort and fatigue: What exactly are we measuring? A British Society of Audiology Cognition in Hearing Special Interest Group 'white paper'

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Abstract

Objective: There is growing interest in the concepts of listening effort and fatigue associated with hearing loss. However, the theoretical underpinnings and clinical meaning of these concepts are unclear. This lack of clarity reflects both the relative immaturity of the field and the fact that research studies investigating listening effort and fatigue have used a variety of methodologies including self-report, behavioural, and physiological measures. *Design:* This discussion paper provides working definitions for listening effort and listening-related fatigue. Using these definitions as a framework, methodologies to assess these constructs are reviewed. *Results:* Although each technique attempts to characterize the same construct (i.e. the clinical presentation of listening effort and fatigue), different assumptions are often made about the nature of these phenomena and their behavioural and physiological manifestations. *Conclusion:* We suggest that researchers consider these assumptions when interpreting their data and, where possible, make predictions based on current theoretical knowledge to add to our understanding of the underlying mechanisms of listening effort and listening-related fatigue.

Foreword

Following recent interest in the cognitive involvement in hearing, the British Society of Audiology (BSA) established a Special Interest Group on Cognition in Hearing in May 2013. In an exploratory group meeting, the ambiguity surrounding listening effort and fatigue was discussed. To address this problem, the group decided to develop a 'white paper' on listening effort and fatigue. This is a discussion document followed by an international set of commentaries from leading researchers in the field. An approach was made to the editor of the International Journal of Audiology who agreed to this suggestion. This paper, and the associated commentaries that follow, are the result.

Key Words: Listening effort; fatigue; measurement techniques; hearing loss

Introduction

For the normal-hearing population, everyday listening is generally a relatively effortless process. When listening in noisy environments, the brain carries out all of the necessary 'backstage operations' that permit the selective processing of a particular sound and simultaneous filtering out of irrelevant information. This has been described as a form of 'selective gain' mechanism (Kerlin et al, 2010). In contrast, for individuals with a hearing loss, listening (aided or unaided) is often reported to be considerably taxing (Kramer et al, 2006). These individuals commonly complain of fatigue associated with the higher levels of concentration or 'effort' required to understand speech in everyday listening environments (e.g. the cafeteria). This increase in the effort required when listening in challenging acoustic environments is thought to give rise to chronic feelings of fatigue and stress (Hetú et al, 1988), which also negatively impact occupational performance by causing more frequent incidences of stress-related sick-leave from work (Kramer et al, 2006). The increased allocation of cognitive resources associated with this heightened 'effort' may also negatively impact one's ability to perform other mental operations during multi-tasking situations (Sarampalis et al, 2009; Anderson Gosselin & Gagné, 2011). Recently, there has been a surge of interest within the audiology profession regarding how

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Abbreviations

EEG	Electroencephalography
ERP	Event-related potential
fMRI	Functional magnetic resonance imaging
RT	Response time
SNR	Signal-to-noise ratio
SSQ scale	Speech, spatial and qualities of hearing scale
WPSS	Wavelet phase synchronization stability

to best characterize and assess listening effort and listening-related fatigue. However, research in the area is still in its infancy and there is considerable disagreement regarding how listening effort should be conceptualized, whether it is a valid construct in the first place, and why and how it is experienced by different listeners.

A reliable measure of listening effort would be of considerable value for those in hearing healthcare. For audiologists, an index of listening effort could complement current clinical assessment tools such as pure-tone audiometry and speech-in-noise tests. By tapping into a consequence of hearing loss not otherwise captured by these standard audiometric techniques, measures of listening effort and fatigue may provide a more comprehensive evaluation of hearing disability for each individual. This knowledge could then be used to:

- inform counselling sessions (e.g. by discussing stress-inducing listening situations for the individual)
- inform intervention strategies (e.g. providing a measure of hearing-aid benefit or allowing comparison between different hearing-aid signal-processing algorithms and/or designs)
- shed light on cases where there is uncertainty about the need for an intervention (e.g. evidence of a borderline disability)

In this paper, we firstly propose working definitions for listening effort and listening-related fatigue. We then describe the various ways in which these concepts are measured in hearing research. Using our definitions as a framework, we review how each method impacts our understanding of both listening effort and listening-related fatigue. While reviewing the literature, we found it helpful to label each measure according to our interpretation of the phenomena that it indexes, before assessing its relation to listening effort or fatigue. See ‘Table 1’ for our categorization of the literature.

What is listening effort?

A standard definition of listening effort has yet to be agreed upon, although it is frequently defined as ‘the attention and cognitive resources required to understand speech’ (Hicks & Tharpe, 2002; Anderson Gosselin & Gagné, 2011; Fraser et al, 2011; Picou et al, 2011). However, speech perception may not be the only type of auditory processing which requires effort. Given the difficulty that hearing-impaired individuals experience with sound source localization and the formation of discrete perceptual auditory objects in a complex auditory scene (Shinn-Cunningham & Best, 2008), it is plausible that additional mental effort would be required in challenging conditions for the perception of environmental sounds (e.g. localizing an ambulance siren) and/or music (e.g. focusing on a particular instrument in an orchestra) as well as speech. The verb ‘to listen’ is defined in the Oxford English dictionary as ‘to give one’s attention to a sound’ (Oxford English Dictionary, 2006). ‘Effort’, on the other hand, is defined as ‘physical or mental exertion’ (Oxford English Dictionary, 2006). Based on these dictionary definitions of its constituent parts, a working definition of listening effort is: *the mental exertion required to attend to, and understand, an auditory message*[1]. Listening may become effortful as a result of sub-optimal conditions at a number of stages, including; (1) a non-canonical or degraded source signal, e.g. accented speech, (2) interference during sound transmission, e.g. background noise, reverberation, hearing-aid signal processing, and/or (3) listener limitations, e.g. hearing impairment, non-native speaker (Mattys et al, 2012). Such interference, however, may be modulated by the presence of a visual aid (i.e. seeing the talker’s face), which has been found to reinforce the executive processing of speech in steady state noise (Mishra et al, 2013).

What is fatigue?

Fatigue is defined as ‘extreme tiredness resulting from mental or physical exertion’ (Oxford English Dictionary, 2006). In the present paper, we focus on ‘mental fatigue’ resulting from effortful listening, which is often reported in individuals with hearing loss (Hetú et al, 1988; Kramer et al, 2006). Reports of listening-related fatigue by individuals with hearing loss provide an incentive for the identification of objective measures of listening effort (i.e. in order to get at the ‘root’ of the problem). However, despite the intuitive link between the effort involved in real-time listening and the (more long term) fatigue that emerges as a consequence of that effort, there is currently little empirical support for this connection within hearing research.

How have listening effort and fatigue been measured?

Measurements of listening effort and fatigue encompass a wide range of techniques. These techniques can be categorized into three main subgroups; (1) self-report, (2) behavioural measures, and (3) physiological measures (Rudner et al, 2012).

Self-reported listening effort

Self-report measures of listening effort often come in the form of a closed-set questionnaire (Gatehouse & Noble, 2004) or rating scale (e.g. Rudner et al, 2012; van Esch et al, 2013). An example of the questionnaire method can be found in the multi-dimensional speech, spatial, and qualities (SSQ) hearing scale (Gatehouse and Noble, 2004) which measures the extent of listening difficulties experienced in various real-world settings, e.g. with and without access to visual cues. Included in the original 49-item inventory are questions that relate to the effort required in everyday listening situations: ‘*Do you have to concentrate very much when listening to someone or something?*’; ‘*Can you easily ignore other sounds when trying to listen to something?*’; and ‘*Do you have to put in a lot of effort to hear what is being said in conversation with others?*’ (Gatehouse & Noble, 2004). Participants give a response on a scale of 0 to 10 with lower numbers indicating more difficulty or effort. For example, in Dawes et al (in press), the authors constructed a ‘listening effort’ subscale from the effort-related questions in the SSQ hearing scale in order to examine changes in listening effort subsequent to acclimatization to hearing aids. New hearing-aid users reported significantly

[1]This working definition is proposed to help refine the focus of this review. For theoretical accounts of the cognitive mechanisms which underlie listening effort, please refer to the subsequent commentaries by Rönnberg and colleagues (2014) and Wingfield (2014) appended to this document.

Table 1. Listening effort studies published 2008–2013 (based on a 'web of knowledge' literature search using the topic 'listening effort' as a keyword) along with their methodology, the authors' outcome measure interpretation, and our interpretation.

Publication	*Method used*	*Authors' outcome interpretation*	*Our interpretation*
Subjective measures			
Panico & Healey (2009)	Listening effort 9-point scale	Mental effort	*Perceived listening effort*
Luts et al (2010)	Listening effort 13-point scale	Listening effort	*Perceived listening effort*
Picou et al (2011)	Listening effort rating scale	Listening effort	*Perceived listening effort*
Brons et al (2012)	Listening effort 9-point scale	Listening effort	*Perceived listening effort*
McAuliffe et al (2012)	Listening effort continuum scale	Perceived listening effort	*Perceived listening effort*
Nagle & Eadie (2012)	Visual analog listening effort scale	Listener effort	*Perceived listening effort*
Rudner et al (2012)	Visual analog listening effort scale	Perceived effort	*Perceived listening effort*
Van Esch et al (2013)	Listening effort 100-point scale	Listening effort	*Perceived listening effort*
Nachtegaal et al (2009)	11-item scale taken from a work assessment questionnaire	Need for recovery after work	*Perceived listening fatigue*
Behavioural measures			
Houben et al (2013)	RT during single-task digit triplets test	Listening effort	*Auditory processing speed*
MacPherson & Akeroyd (2013)[2]	The Glasgow monitoring of uninterrupted speech task (GMUST)	Speech intelligibility in noise	*Auditory processing speed*
Sarampalis et al (2009)	Dual-task paradigm	Listening effort	*Dual-task cost of listening*
Tun et al (2009)	Dual-task paradigm	Perceptual effort	*Dual-task cost of listening*
Howard et al (2010)	Dual-task paradigm	Listening effort	*Dual-task cost of listening*
Anderson Gosselin & Gagné (2011)	Dual-task paradigm	Listening effort	*Dual-task cost of listening*
Fraser et al (2011)	Dual-task paradigm	Listening effort	*Dual-task cost of listening*
Desjardins & Doherty (2013)	Dual-task paradigm	Listening effort	*Dual-task cost of listening*
Hornsby (2013)	Dual-task paradigm: secondary task RT decline across task	Mental fatigue	*Cognitive listening fatigue*
Physiological measures			
Piquado et al (2010)	Pupil response during digit/sentence recall task	Cognitive effort	*Physiological correlate of change in listening demand*
Wild et al (2012)	Brain activation using fMRI during complex speech processing task	Effortful listening	*Physiological correlate of change in listening demand*
Zekveld et al (2010)	Pupil response during SRT task	Processing load	*Physiological correlate of change in listening demand*
Mackersie & Cones (2011)	SCR, skin temperature, electromyographic response and heart rate recordings during dichotic digits task	Listening effort	*Physiological correlate of change in listening demand*
Obleser & Kotz (2011)	Amplitude of the N1 ERP component for processing of degraded speech	Resource allocation	*Physiological correlate of change in listening demand*
Zekveld et al (2011)	Pupil response during SRT task	Cognitive load	*Physiological correlate of change in listening demand*
Koelewijn et al (2012)	Pupil response during SRT task	Listening effort	*Physiological correlate of change in listening demand*
Kramer et al (2012)	Pupil response during a series of auditory and linguistic processing tasks	Processing load	*Physiological correlate of change in listening demand*
Obleser et al (2012)	EEG alpha power during digit memorization task	Cognitive effort	*Physiological correlate of change in listening demand*
Bernarding et al (2013)	Phase-locking of the N1 ERP component during syllable detection paradigm	Listening effort	*Physiological correlate of change in listening demand*
Kuchinsky et al (2013)	Pupil response during a word identification task with varying lexical and acoustic demands	Listening difficulty	*Physiological correlate of change in listening demand*

[2]Although this paper did not appear in the web of knowledge literature search, we felt that it was worth including given its potential use as a behavioural measure of listening effort and/or fatigue over time.

less listening effort after three months of hearing-aid acclimatization compared to a control group of experienced hearing-aid users.

Self-report judgments of effort are also used during experimental listening tasks. In one large-scale study, participants were asked to indicate (on a 100-point scale) how ‘effortful’ they found each particular trial in an auditory profile test battery (van Esch et al, 2013). As expected, hearing-impaired participants gave significantly higher ‘effort’ ratings than their normal-hearing counterparts in all listening conditions. In questionnaire-based ratings, individuals provide a retrospective judgement about the effort involved in everyday listening. In contrast, real-time perceived judgements are given immediately following each listening trial. Such self-report scales are often used in conjunction with physiological techniques (Mackersie & Cones, 2011; Zekveld et al, 2011; Koelewijn et al, 2012).

Self-report measures of listening effort are quick and easy to deliver and do not require particular expertise to administer and interpret. These measures provide an insight into how effortful speech processing is experienced by the individual. However, the limitations of self-report measures stem from their subjective nature. For example, there may be individual differences in effort ‘thresholds’, i.e. what one person finds ‘effortful’ may not equate with another individual’s idea of what constitutes ‘effort’. Larsby et al (2005) suggest that older adults may have a tendency to underestimate their perceived listening effort, based on less extreme self-reported listening effort in elderly subjects compared to younger adults, despite comparably poor behavioural performance in a listening task. Additionally, there may be differences in the interpretation of ‘effort’; some individuals may use task performance accuracy (or task difficulty) rather than mental exertion to inform their self-reported effort rating. Therefore, changes in the mental exertion required to understand an auditory message may go undetected using self-report measures alone.

Self-reported fatigue

Like self-reported listening effort, subjective assessments of fatigue often come in the form of a scale (Nachtegaal et al, 2009) or questionnaire (Kramer et al, 2006). For example, in an open-ended questionnaire-based study investigating the effect of hearing loss on occupational performance, hearing-impaired and normal-hearing workers were administered the ‘Amsterdam checklist for hearing and work’ (Kramer et al, 2006). Hearing-impaired workers were found to be more likely than normal-hearing workers to take sick-leave, citing reasons such as ‘fatigue’ and ‘mental distress’. In Nachtegaal et al (2009), the ‘need for recovery’ scale was adopted to assess fatigue-related difficulties experienced by hearing-impaired individuals at work. This is an 11-item subscale taken from a Dutch questionnaire based on the overall assessment and experience of work. Significantly more hearing-impaired (than normal-hearing) workers reported an increased need for recovery (Nachtegaal et al, 2009).

Perceived fatigue ratings are straightforward to administer and provide first-hand information regarding how ‘fatigued’ the individual feels. Although the source of ‘extreme tiredness’ may be unknown or difficult to pinpoint, it seems unlikely that this kind of subjective experience would go unnoticed by the individual. However, like self-reported listening effort, fatigue ratings may be subject to interpretation differences between individuals. As fatigue reports are given with some degree of hindsight, they may be influenced by an individual’s state of mind at the time of reflection. For example, a subject in a relatively positive state of mind might underestimate the extent of their fatigue and vice versa (DeLuca, 2005).

Behavioural measures of listening effort

Behavioural responses in listening tasks have also been used to index listening effort. Such measures can be categorized into two types; (1) single-task, and (2) multi-tasking paradigms.

Single-task paradigm

In single-task paradigms, participants respond to stimuli either by means of verbally identifying the heard word/sentence (Gatehouse & Gordon, 1990) or by pressing a response button (Houben et al, 2013). Traditionally, when assessing the benefit of amplification to individuals with hearing loss, speech identification in noise performance is assessed by accuracy, i.e. the proportion of correct responses given by the individual in each listening condition. However, it has been suggested that the speed of a correct response may provide additional information regarding the listening effort associated with speech perception (Gatehouse & Gordon, 1990; Houben et al, 2013). In a study by Houben et al (2013), normal-hearing adults performed the digit-triplets task (i.e. identification of three digits) in varying levels of stationary noise. Despite optimal intelligibility, response times were found to be significantly slower in the more challenging signal-to-noise ratios (SNRs). The authors interpret this as reflecting the increased listening effort required to understand speech in difficult acoustic conditions (Houben et al, 2013). Recently, MacPherson and Akeroyd (2013) developed a novel listening task, referred to as the Glasgow monitoring of uninterrupted speech task (GMUST), which may be sensitive to changes in listening effort over time. Rather than presenting listeners with a series of short interrupted sentences, their task involves monitoring continuous speech over several minutes and simultaneously identifying any word substitutions in a written transcript (i.e. cases in which a word in the transcript does not match what was heard).

Response times are believed to correspond with speech processing rate and therefore represent an important factor to consider, as slowed speech processing may significantly impede communication due to the rapid rate of everyday spoken language. Piquado et al (2012) showed that speech comprehension difficulties in hearing-impaired individuals could be alleviated by allowing the participant to control the rate of speech. This behavioural effect may be interpreted as slowed phonological processing and/or lexical access, the impact of which is thought to be modulated by an individual’s working-memory capacity (Rönnberg et al, 2008). However, the relationship between the effort required to understand an auditory stimulus, and the timing of a response to a stimulus, remains unclear. For example, it is equally plausible that an individual may respond more quickly to a stimulus as a result of more focused attention because of the need to exert more cognitive effort to its processing.

Multi-tasking paradigm

Multi-tasking methodologies such as the ‘dual-task’ paradigm originate in cognitive psychology, where they were developed as a measure of attention allocation (Styles, 2006). Kahneman (1973) put forward a ‘limited resource’ account of attention whereby there is only a finite amount of cognitive resources (i.e. ‘energy’) which must be distributed efficiently between various mental operations. When performing two tasks simultaneously, if one (e.g. the primary task) becomes more taxing, this will result in a performance decrement on the other (secondary) task. Secondary task performance may therefore be interpreted as reflecting the amount of effort allocated to the primary task. For measurement of listening effort, a speech recognition task (in varying SNRs) is often used as the primary task (Hicks & Tharpe, 2002; Howard et al, 2010; Anderson Gosselin & Gagné, 2011). Secondary tasks may include, for example, a memory

(Howard et al, 2002), tactile recognition (Anderson Gosselin & Gagné, 2011), or visual recognition (Hicks & Tharpe, 2002) task.

The multi-tasking method appears to have good face validity with regard to speech processing in realistic environments. The efficient execution of multiple simultaneous mental operations is something which pervades much of our daily life, particularly for those in a learning environment. For example, during a classroom lesson, students are often required to attentively follow continuous speech whilst simultaneously taking notes (Howard et al, 2010). However, whilst this method can probe one's ability to divide attention effectively in multi-tasking scenarios, the link between effort and performance relies on certain critical assumptions. It is assumed that the subject's entire resource capacity is always fully utilized for both tasks (i.e. there may be spare cognitive resources not used by either task). It is further assumed that the subject allocates all of his/her remaining resource capacity to the secondary task. However, as there is no independent way of measuring resources dedicated to each task, the argument becomes a circular one (see chapter 6, Styles, 2006 for discussion). For example, an individual may decide to allocate most of their attention to the more novel task (perhaps unconsciously), regardless of instructions to prioritize one task over the other. Children, in particular, are commonly found to demonstrate this task 'bias' (e.g. Choi et al, 2008), and this may limit the task's application to this population. With respect to its more recent use in hearing research, the multi-tasking method may shed light on the behavioural cost of listening in adverse conditions. However, it remains unclear whether secondary task performance actually constitutes an objective index of listening effort (i.e. 'mental exertion') *per se*.

Behavioural measures of fatigue

Behaviourally, mental fatigue is characterized as the 'slowing' or decline of cognitive functions following concerted and/or prolonged mental effort (DeLuca, 2005). This decline is typically detected using a vigilance task in which the subject sustains his/her attention for a prolonged period of time. For example, in Bryant et al (2004), performance declines were found in individuals with multiple sclerosis and healthy controls towards the latter stages of a continuous working memory task. However, only one study (to date) has used this methodology to assess fatigue in a listening effort task. Hornsby (2013) used self-report and behavioural measures of listening effort and fatigue in a dual-task study with hearing-impaired participants. Word recognition served as the primary task with both visual response time and word recall as secondary tasks. Listening effort was indexed by average visual response time and word recall performance in unaided versus aided conditions, whereas fatigue was indexed as the relative increase in visual task response time (i.e. response slowing) over the duration of each one-hour aided and unaided trial block. Both listening effort (indexed by average visual response time and word recall performance) and mental fatigue (indexed by the slowing of response times over the duration of each block) were found to be reduced in aided, as compared to unaided, listening conditions. This was taken to reflect an increase in effort-induced cognitive fatigue in unaided listening conditions (Hornsby, 2013).

Hornsby's (2013) finding provides the first empirical link in the assumed relationship between repeated incidences of effortful listening and subsequent cognitive fatigue. However, self-report measures of fatigue taken before and after each block of trials did not show the same change between aided and unaided conditions. Hornsby (2013) suggests that this reflects the fact that self-report and behavioural measures assess separate aspects of fatigue. Another possibility is that self-reported fatigue measures were affected by subjective biases. For example, there may be individual differences in fatigue thresholds or in the interpretation of the fatigue-related question asked. Overall, more research is needed to ascertain the extent to which this behavioural effect of impaired vigilance is causally related to reports of 'extreme tiredness' from individuals with hearing loss.

Physiological measures of listening effort

Physiological measures refer to the recording of changes in central and/or autonomic nervous system activity during task performance. Listening effort-related changes in central nervous system activity have been investigated using functional magnetic resonance imaging (fMRI), electroencephalography (EEG), and event-related potentials (ERPs). Autonomic nervous system activity has also been examined for evidence of listening effort-related changes, including changes in skin conductance and pupil dilation. Such experiments typically involve a behavioural task with a number of conditions which vary in degree of difficulty. Assuming comparable behavioural performance between conditions, any systematic physiological changes that occur in the more-challenging condition/s are generally attributed to listening effort.

Functional magnetic resonance imaging (fMRI)

fMRI is a neuro-imaging technique that provides information about brain activity by exploiting metabolic consequences of neuronal activity and the resulting changes in blood oxygenation level. In particular, this technique has been used to assess the role of attention in effortful listening. Wild et al (2012) used fMRI to compare processing of noise-vocoded versus clear sentence stimuli (amongst visual and auditory distracters). Increased activity in the left inferior frontal gyrus was found when participants were required to attend to degraded speech, as compared to clear speech. This was interpreted as reflecting the compensatory effort required to perform challenging listening tasks.

Given the sample and the experimental procedure used in Wild et al's (2012) study (normal-hearing individuals and noise-vocoded speech), it is still unclear whether this activation corresponds to the kind of mental exertion experienced during every-day listening by hearing-impaired individuals. Further research with hearing-impaired individuals in which realistic listening environments are simulated may elucidate whether this kind of increase in frontal activity is indicative of listening effort.

Electroencephalography (EEG)

Cortical EEG involves measuring electric potential fluctuations associated with neural activity through a series of electrodes placed directly on the scalp. EEG activity is generally categorized in terms of the frequency 'band' to which particular oscillations (regular waveform fluctuations) belong. These include; delta (< 4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (14–30 Hz), and gamma (> 40 Hz) bands. Previous studies have selectively examined each frequency band for potential neural correlates of specific cognitive processes. For example, theta activity has been interpreted as reflecting memory processing, and beta activity is thought to be associated with motor responses (Sauseng & Klimesch, 2008). Alpha activity has received attention from researchers interested in how speech is processed in adverse conditions, as it is believed to reflect the functional inhibition associated with effortful listening (i.e. the suppression of activity in areas of the brain not functionally involved in stimulus processing) (Sauseng & Klimesch, 2008).

Obleser et al (2012) manipulated both memory load and auditory stimulus degradation (using noise-vocoding techniques) in an auditory working-memory task. Participants were required to give a response indicating whether a particular digit had been presented during a long sequence of digits. Increased alpha power was found during the memorization period in right parietal, cingulate, supramarginal, and superior temporal cortex both for increased memory load conditions and conditions with more-degraded auditory stimuli. The authors interpreted this as evidence for an integrated alpha oscillatory network which incorporates multiple aspects of processing such as the perceptual ease of speech understanding and short-term memory storage. Obleser et al (2012) suggested therefore that alpha oscillatory power may reflect increased listening effort in difficult listening conditions, such as those routinely experienced by hearing-impaired listeners.

Using similar spectrally-degraded speech stimuli, an earlier study by Obleser and Kotz (2011) showed earlier peaks and increased amplitude of the N1 ERP component (a negative polarity potential occurring 100 ms post stimulus-onset) when processing more-degraded speech, compared to less-degraded speech. This was interpreted as reflecting increased 'neural effort' to decode the degraded message (Obleser & Kotz, 2011). Other researchers have investigated phase synchronization of the N1 component. Phase synchronization refers to how well single sweeps in a particular condition are time-locked across successive trials. Bernarding et al (2012) manipulated the difficulty of an auditory syllable-detection task by presenting the target syllable simultaneously with syllables that either sounded similar (difficult condition) or sounded different (easy condition). The phase synchronization of the N1 component systematically increased with increasing task difficulty. This was interpreted as reflecting the increased listening effort required to perform the more challenging auditory task (Bernarding et al, 2012).

EEG measures provide temporally-precise markers of mental processing (Obleser and Kotz, 2011; Bernarding et al, 2012; Obleser et al, 2012) with a temporal resolution at the millisecond level. EEG information such as phase characteristics and amplitude of the N1 component may provide insights into aspects of cognitive processing (e.g. selectively attending to a particular stimulus) which may be implicated in listening effort. However, it remains unclear whether these markers can tell us about the kind of 'mental exertion' likely to give rise to the chronic experience of fatigue and tiredness in hearing-impaired individuals. In order to make this connection, it may be worthwhile to look at changes in spectral or temporal characteristics over the time period during which fatigue may be induced (in the order of minutes/hours).

Pupillometry

The changing size of the eye's pupil is controlled by muscle activity in the iris. Pupil size fluctuates as an adaptive response to changes in the environment (e.g. the 'light reflex'). However, fluctuations in pupil size may also be elicited by changes in mental task load (Kahneman, 1973). As pupil size reflects activity in the sub-cortical structure 'locus coeruleus', it is also thought to be modulated by changes in attention, stress, and memory (Laeng et al, 2012). In a study by Zekveld et al (2011), older and hearing-impaired adults showed less of a decrease in pupil size from difficult to easier listening conditions compared to their younger normal-hearing counterparts. The authors suggested that this reflects less 'release from effort' in the older and hearing-impaired adults compared to the younger adults in easier listening conditions (Zekveld et al, 2011). Pupil responses have also been shown to vary systematically according to the type of noise masker used. Listening to speech in the presence of an informational masker (e.g. a single-talker masker) was associated with larger peak dilations than listening conditions which involved maskers with the same energetic level of masking, but lower informational content (e.g. fluctuating noise) (Koelewijn et al, 2012).

Pupillometric methods have been used to show changes as a function of listening task demand in clinical (Zekveld et al, 2011) and non-clinical (Zekveld et al, 2010; Koelewijn et al, 2012; Kramer et al, 2012) populations. However, the interpretation of changes in pupil size in different populations is not straightforward. Older adults have been shown to have relatively small absolute pupil sizes (Zekveld et al, 2011) which may influence the extent to which a significant change in pupil size can be recorded. In contrast, children show larger absolute pupil sizes. This is suggested to reflect a higher state of general arousal during novel experimental task situations than is typically found in adults (Karatekin, 2004). To address this point, some studies have normalized pupil size; thus enabling comparison between groups (e.g. Piquado et al, 2010). Overall, in well-controlled experimental settings, relative changes in pupil size may reflect systematic changes in 'mental exertion' not otherwise captured using behavioural measures alone.

Skin conductance

Skin conductance reflects the amount of moisture on the surface of the skin and is assessed by measuring the skin's capacity to conduct an electrical current (Boucsein, 1992). Measurement is made from the eccrine sweat glands which are predominantly found on the palm of the hands or the soles of the feet. As with the pupil response, changes in the amount of moisture produced by these sweat glands are influenced by parasympathetic and sympathetic activity reflecting changes in arousal. Mackersie & Cones (2011) gave normal-hearing young adults a dichotic-digits task in which task difficulty was manipulated by varying the number of digits for recall and whether digits were presented to one ear or both ears simultaneously. Throughout this task, skin conductance was recorded. Digit recall accuracy was similar across conditions, but significantly higher skin conductance responses were found for medium- and high-demand listening conditions. Changes in skin conductance also appeared to be reasonably consistent at the individual level. Sixty percent of participants showed significant skin conductance changes from low- to medium- and high-demand conditions (Mackersie & Cones, 2011). The authors found a correlation ($r = 0.67$) between changes in skin conductance and self-reported listening effort across task demand (Mackersie & Cones, 2011). Other physiological measures were included in this study (skin temperature, frontalis muscle activity, and heart rate), with only muscle activity showing significant task-related changes. However, these changes in muscle activity were not found to be as consistent across individual participants as skin conductance.

As a relatively new approach to measuring listening effort, these findings have yet to be replicated in other more complex speech processing tasks. It remains to be seen how reliably changes in autonomic activity reflect individual differences in mental exertion while listening in everyday situations. As this is a non-invasive task which is easy to administer while participants concurrently perform a listening task, it may be a useful measure in individuals for whom it is difficult to obtain reliable behavioural data (e.g. individuals with physical disabilities).

Physiological measures of fatigue

To our knowledge, only one attempt at measuring listening-related fatigue using physiological techniques has been made. Hicks and Tharpe (2002) examined differences in cortisol levels between hearing-impaired and normal-hearing children for potential markers of fatigue. Cortisol is an adreno-cortical hormone produced in response to stressors, and cortisol levels can be obtained by analysing salivary samples. High cortisol levels are typically associated with stress, while low cortisol levels are associated with fatigue (Hicks & Tharpe, 2002). Salivary samples were taken at the beginning and end of the school day and no significant differences in average cortisol levels were found between hearing-impaired and normal-hearing children. The authors present a number of possible explanations for the lack of an effect, including: (1) limited sensitivity of the measurement technique, (2) increased stressful listening has not yet accumulated to fatigue in these children, and/or (3) amplification (used routinely in the majority of participants) reduced stress and fatigue (Hicks & Tharpe, 2002).

General Discussion

There is growing interest amongst researchers and clinicians in listening effort and fatigue, with numerous attempts to characterize these phenomena in a laboratory setting. Although research output has increased, progress has been hampered by extensive disagreement about the nature of listening effort, and its validity as a measurable construct. This has resulted in a proliferation of putative measures of listening effort/fatigue with consequent ambiguity regarding their interpretation and relationship to each other as well as considerable confusion over the terminology associated with each measure. Different terminology is often used to describe observations obtained using the same methodological approach. For example, Zekveld et al (2011), Koelewijn et al (2012), Kramer et al (2012), and Piquado et al (2010) all used pupillometric techniques to measure differences in 'cognitive load', 'listening effort', 'processing load', and 'cognitive effort', respectively. There are also consistent findings of weak (or no) relationship between: (1) self-report and dual-task measures of listening effort (Anderson Gosselin & Gagné, 2011), (2) self-reported listening effort and speech recognition task difficulty (Larsby et al, 2005), (3) self-report and physiological measures of listening effort (Zekveld et al, 2010, 2011), and (4) self-report and behavioural measures of fatigue (Hornsby, 2013).

As self-report measures remain an important factor in deciding clinical significance, the lack of any correlation between apparently related constructs suggests that we may be missing whatever it is about listening effort and fatigue that is important to the individual. There may, however, be several other explanations for the inconsistencies presented above. The thread that connects many of the studies reviewed in this discussion paper is the manipulation of task difficulty, assumed to modulate listening effort. In some cases, perhaps the implicit assumption that task difficulty is directly related to listening effort requires closer inspection. There may be other criteria that some experimental paradigms simply do not meet. For example, whilst a listening task should not exceed the listener's capabilities, the experimental manipulation should require (at least to some extent) mental exertion from the listener.

The confusion surrounding listening effort and fatigue is a by-product of a more pertinent issue regarding the underlying assumptions tied to each methodology. As we have described, listening effort has been differentially measured using self-report, behavioural, and physiological techniques. Each method is generally used to measure the same construct – that is, the clinical presentation of listening effort or fatigue. As such, researchers must make the following assumptions about each measure; (1) for self-report measures of listening effort, the experience of listening effort will be accurately perceived and recognized (either in real-time, or in hindsight), (2) for single-task paradigms, 'mental exertion' is causally related to time-spent on a listening task, (3) for the multi-tasking paradigm, 'mental exertion' during listening reflects the taxing of a limited-capacity system, and this 'mental exertion' will reveal itself as a secondary task performance decrement, and finally (4) for physiological techniques, the particular processes being monitored actually mimic the physiological mechanisms that underpin listening effort. We suggest that researchers consider these assumptions and conduct experiments that are guided by predictions based on current theoretical knowledge. For example, further research investigating the cognitive factors (e.g. working-memory capacity) which predict effortful listening under certain listening conditions could allow testing of Rönnberg and colleagues (2008) ease of language understanding (ELU) model (discussed in detail in the accompanying commentary by the same authors). This may shed light on the discrepant findings discussed in this paper and add to our current understanding of this topic.

Conclusion

Due to a lack of clarity regarding the theoretical underpinnings of listening effort and listening-related fatigue in the literature, we provide working definitions for these constructs. In our opinion, it is important to clarify these terms based on the general principle that the mental exertion required to understand speech in sub-optimal listening conditions may detract from other cognitive activities and/or lead to feelings of fatigue and stress in those affected. Using these definitions as a framework, this paper highlights the critical assumptions made by researchers using self-report, behavioural, and physiological techniques to measure listening effort and listening-related fatigue. We suggest that researchers develop research questions that are informed by existing theoretical knowledge regarding the interplay of cognitive processes during speech understanding in adverse conditions to further research progress in the area.

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Abbreviations

EF	Executive function
ELU	Ease-of-language understanding
RAMBPHO	Rapidly, automatically, and multimodally bound into a phonological representation
SIC	Size comparison
WMC	Working memory capacity

Let us begin by commending the authors for bringing up the issues of listening effort and fatigue for international discussion. Undoubtedly, listening effort and fatigue are clinically important notions but the question is whether they bear theoretical weight. We will in our commentary focus on listening effort but some of the issues we raise may also have a bearing on fatigue.

The definition that is endorsed by the author team is dictionary-based: Listening effort is the 'mental exertion required to attend to, and understand, an auditory message'. While this may be a good layman's definition, we argue that it is impossible to fully understand the notion of listening effort without addressing the cognitive mechanisms involved in mental exertion. Given a theoretical account of a mechanism involved, any measurement procedure or technique has to take into account the possible constraints on that mechanism.

One such mechanism, "ease-of-language understanding" (ELU), has been described in the model of the same name (Rönnberg, 2003, Rönnberg et al, 2008) and the concept of effort was explicitly addressed in the Rönnberg et al (2013) update of the model. Ease is the absence of effort. The ELU-model assumes that under ideal listening conditions, spoken input is rapidly, automatically, and multimodally bound into a phonological representation (RAMBPHO) that—given that a sufficient number of perceived phonological attributes (i.e. above threshold) *matches* the phonological representations in semantic long-term memory—allows the rapid, implicit and automatic unlocking of lexical representations and their corresponding meaning. When there is a *mismatch* (e.g. due to noise, reverberation, suboptimal signal processing in the hearing aid, or due to the hearing impairment itself), explicit cognitive resources "kick in" to support listening by allowing reconstruction of fragmented phrases and inference-making (Rönnberg et al, 2010). Explicit resources typically studied in this context are working memory capacity (WMC) and executive functions (EF) (Rönnberg et al, 2013; Rudner et al, 2011; Mishra et al, 2013). While the implicit processing mechanism is rapid and predictive, the explicit processing mechanism is relatively slow, deliberate, and postdictive. Both interact in a forward analysis-by-synthesis manner. The degree to which explicit processes are engaged is assumed to reflect the "effort" involved in tracking and/or reconstructing, e.g. what a talker says in a multi-talker situation at a cocktail party.

So, the general prediction based on the ELU-model is that "mismatching" conditions during language understanding will reduce ease and thus by implication increase effort. In this context, a high WMC will help compensate for mismatch whether it arises from poor input signals (Foo et al, 2007; Lunner, 2003; Rudner et al, 2009) or poor representations in long term memory (Classon et al, 2013), thus increasing ease of language understanding and reducing effort.

Empirically, there is support for the idea that higher WMC is associated with lower perceived (subjectively rated) effort, at least for tasks of intermediate levels of difficulty (Rudner et al, 2012). When task difficulty hits the ceiling or the floor, there is less room for WMC to be predictive of effort (Rönnberg, 2003). Thus, generally speaking, task conditions that invoke explicit processing mechanisms seem to be one prerequisite for experiencing effort (cf. Ng et al, 2013). On top of that, the degree of effort actually experienced by the individual is determined by WMC.

Apart from behavioral measures, there are several brain-based means of investigating mental effort. As commented on in the "white paper" pupil size has recently been suggested to index cognitive load and associated effort. Pupil size is among other things affected by chronological age (Zekveld et al, 2011), level of intelligibility of a spoken signal (i.e. lower levels giving larger pupil size, Koelewijn et al, 2012a), and noise masker type (i.e. fluctuating maskers causing similar levels of pupil size as stationary noise, but single-talker maskers causing larger pupil size, see Koelewijn et al, 2012a,b; Zekveld et al, in press). Interestingly, Koelewijn et al (2012b) found that better size comparison span (i.e. SIC span), which is a measure of inhibition in working memory (Sörqvist & Rönnberg, 2012), was associated not only with higher performance in the single-talker condition, but also with a larger pupil size.

This pattern of findings was suggested to show that high WMC—indexed by SIC span—actually causes a higher mental load (Van der Meer et al, 2010; Zekveld et al, 2011). However, the increase in pupil size may reflect a more extensive or intensive use of brain networks (Koelewijn et al, 2012b; see Grady, 2012) rather than an increase in the actual load, although, other studies show that smaller pupil sizes are observed in individuals with high WMC when performing the reading span task (Heitz et al, 2008).

One solution to these conflicting interpretations could be that investing effort in performing a reading span task may in itself be qualitatively different from investing effort in understanding speech in adverse listening conditions (Mishra et al, 2013). Although a person with high WMC may show smaller pupil dilation than a person with low WMC during a WM task, the person with high WMC may show larger pupil size during a task that requires communication under adverse conditions, even if memory load is comparable, simply because WM resources can be more usefully deployed. The reason behind may be that there is no obvious upper limit to how adverse listening conditions can get before understanding speech breaks down. The brain probably makes the most of its available resources to understand speech (cf. Reuter-Lorentz & Cappell, 2008; Wong et al, 2009).

What has not been suggested in the "white paper" is that another way of estimating effort is to measure episodic memory for what was said rather than using on-line estimates such as the pupil size. Given that an episodic memory outcome variable reflects the effort invested in the initial speech-in-noise task, then there should be an inverse relationship between the need to deploy mental resources to language comprehension and the parallel capacity for encoding into episodic long-term memory (Classon et al, 2013). Again, WMC would be expected to modulate that effect (Classon et al, 2013).

This is exactly what was found in the Sörqvist and Rönnberg (2013) study, where it was demonstrated that episodic long-term memory for spoken discourse was more negatively affected by a speech masker compared to a rotated speech masker. Furthermore, in hierarchical regression analyses it was shown that after having controlled for initial hearing levels, there was still an episodic long-term memory effect specific to the speech masker condition that was modulated by WMC. In particular, the SIC span task—which taps into EF in the sense that inhibition capacity needs to be used to resolve semantic confusion at retrieval—was a statistically reliable predictor of delayed recall from episodic long-term memory.

Along the same lines, Zekveld et al (2013) found that the benefit of providing semantic cues during speech-in-noise understanding in a single-talker masker condition was also related to WMC. Interestingly enough, WMC again predicted delayed episodic recognition memory for sentences, when semantic cue benefit was accounted for.

The results generally imply that WMC is associated with release from informational masking and that this capacity also is associated with semantic encoding and retrieval from episodic long-term memory.

Conclusion

Many of the conclusions in the "white paper" point to the fact that there either exist rival interpretations or rival findings for the behavioral and neuroscience approaches used to estimate "effort". In this short commentary we have taken the approach to suggest that recent findings in the literature can actually be used to understand "effort" in terms of on-line demands on WMC while understanding speech in adverse conditions, as well as the resulting long-term episodic memory functions modulated by WMC.

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There has been an increasing recognition in hearing research that attempting to understand hearing acuity and its amelioration independently from the end-product cognitive operations represents an artificial, and arguably counterproductive, separation. This recognition has appeared along with terms such as "cognitive hearing science" (Arlinger et al, 2009) and "cognitive audiology" (Jerger, cited in Fabry, 2011, p. 20). McGarrigle and colleagues' "white paper" is written in this spirit, with the goal of assessing the state of the science on the concepts of *listening effort* and *fatigue* in the context of hearing impairment, and potential indices of effort and fatigue that might find a place in audiometric evaluation.

Although with differences in emphasis from one theorist to another, there is a common acceptance in experimental psychology that individuals possess limited cognitive resources (the terms *attentional resources* or *processing resources* are often used interchangeably) that must be allocated among multiple inputs or activities. As articulated by Kahneman (1973) and Broadbent (1971), albeit using different metaphors, there is a reciprocal relationship between the degree of cognitive and/or perceptual demands required for successful completion of one task and the likelihood of effective performance of another task performed simultaneously or overlapping with the first.

It should be noted that the assumption of a single pool of resources has not always been accepted. *Multiprocessor models* of attention have considered the possibility of a number of independent processing operations with separate resources, with the interference effects one observes being due to the effort required to separate the processing streams (Allport et al, 1972; McLeod, 1977). The implication is that simply finding that performing two simultaneous or overlapping perceptual or cognitive operations are more difficult than performing a single task does not necessarily support a single-resource model such as Kahneman's or Broadbent's. Rather, one would need to show that independently increasing the difficulty in incremental steps of each of two tasks when performed alone, will show an incremental, step-wise decrease in performance on one or both tasks when the two are performed together (Kerr, 1973). This is a high bar to pass for a test of a single-resource theory, especially, as Kahneman has argued, resources may be limited, but not necessarily fixed. This is a suggestion that greater effort may increase the amount of available resources, at least temporarily (Kahneman, 1973).

This level of nuanced argument is absent from the white paper, which adopts without comment the current assumption of a single allocateable resource model. There are good reasons, however, for doing so. The single-resource model has stood the test of time for its descriptive utility and it remains the dominant if not uniform model assumption in the literature.

At the behavioral level there is little question that cognitively and/or perceptually challenging tasks are subjectively more effortful, that they reveal physiological changes, such as an increase in the pupil size of the eye (Piquado et al, 2010; Zekveld et al, 2011) and changes in the pattern of neural activation in imaging studies (Peelle et al, 2010). Of immediate importance, such processing challenges take a significant toll on performance, whether in terms of dual-task interference (Sarampalis et al, 2009; Tun et al, 2009), memory for what has been heard (Murphy et al, 2000; Rabbitt, 1991; Surprenant, 1999; Wingfield et al, 2005), or comprehension of rapid and syntactically complex speech (Wingfield et al, 2006).

The general notion of *resources* and *effort* appeared in the literature well over 100 years ago, with Titchener's (1908) reference to the limited capacity of what he referred to as "psychic energy", and the perceptual consequences of its differential allocation. He describes in his monograph the way in which individuals can allocate attentional effort to perceptually isolate (and subjectively amplify) the 'voices' of individual instruments in an orchestral concert. Having done this, however, he also recognized the difficulty of going beyond a simple description of effects. As he put it: "The discovery of attention [by the psychologists] did not result in any triumph of the experimental method. It was something like the discovery of a hornet's nest; the first touch brought out a whole swarm of insistent problems." (p. 173).

Some 100 years later, are we closer to defining "resources" and "effort", or indeed, "attention"? Cognitive psychology as a field has yet to settle on the relationship between working memory, executive function, and resources. Some theorists place emphasis on a central executive as a single resource overseeing the storage and manipulation of recent, or recently activated, sensory input or memory traces, while others emphasize a complex system that controls such additional operations as maintaining the focus of attention, set shifting, updating working memory, and inhibition (cf. Baddeley & Logie, 1999; Cowan, 1999; Engle, 2002; McCabe et al, 2010; Miyake et al, 2000). Indeed, in describing cognitive support for the perception of degraded speech, reference is sometimes made to utilization of working memory, which itself might require effort, where others might make reference to resources or to executive control (see for example, Rönnberg et al, 2010, 2011).

By defining *listening effort* in operational terms as, "The mental exertion required to attend to, and understand, an auditory message", the white paper stays above the theoretical fray, accepting the general principle that perceptual challenge or multi-tasking draws on resources that, among other things, may have a negative impact on other activities and may cause a sense of mental fatigue. Both from the literature and one's own experience this is clearly the case.

It should be said that there are numerous examples in science of agreed-upon and useful measurements of consequences of underlying mechanisms even as these underlying mechanisms may be poorly understood. As one considers the indices of listening effort described in this white paper (self-report, behavioral measures, such as dual-task interference, and the cited physiological measures), only self-reports would seem to have immediate practicality for potential use in the hearing clinic. The other measures, while good research tools, are unlikely to see near-future widespread use in the audiology clinic for logistical reasons and the time and expertise required for their interpretation.

As the white paper notes, subjective reports, whether open-ended or in questionnaire format, are not perfect instruments. Notably, they are susceptible to individual differences in how one understands the questions and differences in individuals' internal reference scales. Yet subjective reports of effort and mental fatigue are not without value. If one may draw an analogy, it is the physician who just "looks at the numbers" to decide on a patient's physical state versus the physician who also looks at how the patient stands, walks, and smiles to assess the patient's health. It is the case that two individuals may be able to identify a spoken word at the same amplitude or level of background noise. In the laboratory good experimentalists will often also measure latencies to giving the correct responses, as this may reveal differences in processing difficulty for two stimuli both of which were correctly identified. In the same way, two different signal processing algorithms in an amplification devise may give equal success in word recognition under various background conditions. It may not be the case, however, that this success is accomplished with the same level of effort. As clearly described in the white paper, more effortful versus less effortful perception can result in degraded performance as well as inducing mental fatigue.

The white paper under discussion does not add to our theoretical understanding of sensory-cognitive interactions in effortful listening or how this translates into the subjective experience of mental fatigue or objective decline in task performance. It does, however, reflect the increasing recognition of their importance, and the desired goal of developing objective, clinically relevant, tests of listening effort (e.g. Rönnberg et al, 2011). Of special value is the ability to assess degrees of listening effort consequent to different signal processing algorithms in a hearing aid beyond whether or not the identity of a stimulus can be correctly reported (Sarampalis et al, 2009).

Especially important in this regard is attention to the demands for good psychometric test development, not the least of which is test-retest reliability.

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Response to commentaries

We are grateful to the authors for their insightful commentaries on our discussion article. Rönnberg and colleagues present a compelling case for the interpretation of listening effort within an integrated model which details the cognitive mechanisms involved when listening in adverse conditions. The role of working-memory capacity in language comprehension ability has gained substantive empirical support (Daneman & Merikle, 1996) and forms an important component of Rönnberg and colleagues’ ease of language understanding (ELU) model. However, while there is general agreement regarding the existence of some limited-capacity mechanism that influences (and is influenced by) representations in long-term memory, the particular emphasis and terminology assigned to each operation (e.g. working-memory, resources, executive function) differs for proponents of each theory (Baddeley, 2012). Wingfield mentions this conflict in his commentary and articulately reflects on the progress that has been made in the last century within cognitive psychology and related areas surrounding the concept of effort (or, as originally termed, ‘psychic energy’). In doing so, Wingfield reminds us that our understanding of the interplay of cognitive functions during perceptually-challenging speech processing is far from complete and that there are various competing theoretical accounts.

Listening effort may be influenced not only by the cognitive processes that underpin speech processing, but also by the individual’s language system itself. Recent work in psycholinguistics has highlighted some important individual differences in how lexical items are mentally represented (and accessed) during comprehension. Perfetti (2007) proposes the lexical quality hypothesis to capture this individual variation. Differences in the strengths of the mappings between elements of a lexical item (e.g. between phonological form and meaning) have been shown to lead to processing differences reflected in eye fixation times on words during reading (Kuperman & Van Dyke, 2011) and event-related brain potentials (Perfetti et al, 2005). Individuals with lower quality lexical representations find it harder to process words. It is likely that such differences in the quality of a listener’s lexical representations will impact the effort required for successful speech comprehension. Any model of speech understanding should therefore be able to allow for the moderating influence of such differences on listening effort. By entering the ‘theoretical fray’, audiologists can make an important contribution to understanding these processes as well as achieving a more complete understanding of the communication difficulties faced by their patients.

Wingfield suggests that the various techniques listed in the discussion paper might be useful in lab-based explorations of listening effort, but that only self-report measures are currently practical for use in clinical settings. Researchers should therefore consider including self-report measures alongside other measures in order to better understand the strengths and limitations of the self-report tools currently available to audiologists in the clinic. We are grateful that Wingfield's commentary will form part of the overall document, since it provides a fitting overview of theoretical developments and conflicts stemming from the field of cognitive psychology which inform our current understanding of listening effort and fatigue. We are also grateful that Rönnberg and colleagues draw the readers' attention to their ELU model. Such models could have valuable explanatory and predictive power and help to provide direction and focus for future research in the area. For alternative models of speech perception, we direct readers to: McClelland and Elman's (1986) TRACE model, Marslen-Wilson's (1987) cohort model, Luce and Pisoni's (1998) neighbourhood activation model, and Poeppel et al's (2008) 'analysis-by-synthesis' approach.

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