Use of a Dual-Task Paradigm to Measure Listening Effort

Utilisation d'un paradigme de double tâche pour mesurer l'attention auditive

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Abstract

Listening effort is an important dimension of speech understanding. Despite the fact that a significant amount of speech understanding involves cognitive processes, much of clinical audiology remains focused on assessing the auditory periphery. As speakers age, their sensory, perceptual and cognitive functions decline. It has been speculated that older adults exert increased listening effort compared to younger adults but this effect is still poorly understood. Listening effort refers to the attention and cognitive resources required to understand speech. Listening effort can be evaluated indirectly in clinical practice through self-report, or it can be quantified more objectively using a dual-task paradigm. This paper emphasizes the importance of measuring listening effort and reviews the literature. The review focuses on dual task paradigms which have been used to investigate the effort related to understanding speech. The paper concludes with a discussion of the clinical importance of measuring listening effort.

Abrégé

L'attention auditive est une dimension importante de la compréhension de la parole. Même si la compréhension de la parole repose essentiellement sur des processus cognitifs, l'audiologie clinique se concentre en grande partie sur l'évaluation de la périphérie auditive. En vieillissant, les fonctions sensorielles, perceptives et cognitives des locuteurs diminuent. Il a été spéculé que les adultes plus âgés se fatiguent davantage lorsqu'ils doivent faire preuve d'une plus grande attention auditive comparativement aux adultes plus jeunes, mais cette hypothèse quant aux effets de l'âge est encore mal compris. L'attention auditive désigne l'attention et les ressources cognitives nécessaires pour comprendre la parole. Cet effort peut être évalué indirectement en pratique clinique à l'aide d'une auto-évaluation, ou il peut être quantifié de façon plus objective en utilisant un paradigme de double tâche. Cet article met l'accent sur l'importance de mesurer l'attention auditive et passe en revue la littérature. La présente revue est axée sur les paradigmes de double tâche qui ont été utilisés pour étudier l'attention liée à la compréhension de la parole. L'article se termine par une discussion sur l'importance clinique de mesurer l'attention auditive.

Key words: listening effort, dual-task paradigm, cognition, aging, speech perception, hearing loss, hearing aids, rehabilitation

Abbreviations

A: Auditory
ANL: Acceptable Noise Level Test
AV: Audio-visual
BKB-SIN: Bamford-Kowal-Bench Speech in Noise Test
BNL: Background noise level
CHABA: Committee on Hearing and Bioacoustics and Biomechanics
CID: Central Institute for the Deaf
HHIA: Hearing Handicap Inventory for Adults
HHIE: Hearing Handicap Inventory for the Elderly
HINT: Hearing in Noise Test
ICF: International Classification of Functioning, Disability and Health
IOI-HA: International Outcome Inventory for Hearing Aids
MCL: Most comfortable level
pDTC: Proportional dual task cost
QuickSIN: Quick Speech in Noise Test
SNR: Signal-to-noise ratio
SSQ: Speech, Spatial and Qualities of Hearing Scale
SVIPS: Speech and Visual Information Processing System
WHO: World Health Organization
WIN: Words in Noise Test

Hearing and listening are different

Audiologists routinely measure hearing ability. However, there is more to communication than simply hearing. The process of communication involves not only perceptual factors like the ability to hear but also cognitive factors (Kiessling et al., 2003; Worrall & Hickson, 2003). In 2001, the hearing aid company Oticon assembled an international panel of experts to discuss the delivery of audiological services to older adults. Taking inspiration from the World Health Organization's International Classification of Functioning, Disability and Health (ICF; WHO, 2001), the group found that the traditional term "hearing" must be understood to involve hearing, listening, comprehending and communicating (Kiessling et al., 2003). This expanded definition of "hearing" recognizes the contributions of peripheral and central factors and acknowledges the fundamental difference between hearing and listening. Hearing is a sense (a passive function) but listening is a skill that requires attention and intention to access and use the information that is heard. Comprehension involves the reception and interpretation of the meaning and intent of the information. Communicating involves the effective use and transfer of information.

This paper focuses on the distinction between hearing and listening with an emphasis on the listening effort involved with listening comprehension. The importance of measuring listening effort and the influence that age and hearing impairment have on listening effort is explained. Subjective and objective measures of listening effort are detailed, including the mechanics of dual task-paradigms that can be used as an objective means to assess listening effort behaviourally. Next, a review of the literature related to the dual-task paradigm as a measure for the effort related to speech understanding is presented. The paper concludes with a discussion of the clinical importance of measuring listening effort.

The importance of measuring listening effort

To illustrate the importance of distinguishing hearing from listening, let us consider two hypothetical (but realistic) case studies with similar hearing ability but varying degrees of difficulty in day-to-day listening and communication situations. Client A has a moderate sensorineural hearing loss bilaterally and wears two hearing aids. Masked word discrimination ability was measured at 68% and 72% for the right and left ears respectively. Even with amplification, Client A has marked difficulties understanding speech in noisy situations and hearing the television clearly at a normal volume level. Over the years, Client A has slowly started to withdraw from social situations as he feels tired and stressed at the end of the day, when he has had to concentrate hard on listening. In contrast, a second Client B has a moderate to severe sensorineural hearing loss bilaterally and uses a combination of hearing aids and assistive listening devices. Her word discrimination ability is equivalent to Client A. Client B has minimal difficulties hearing in noise because she uses an FM system. Client B continues to have some difficulties hearing telephone conversations clearly, even when using her telecoil settings and volume control. She continues to work full-time and has a very active family and social life.

If we use the ICF model (WHO, 2001) to interpret these hypothetical cases, we find that Client A has more activity limitations and participation restrictions than Client B. However, these important differences would be invisible to an audiologist who only relied on traditional measures such as the audiogram or standardized speech tests.

In clinical practice, speech understanding is evaluated using a standardized word recognition test (e.g., CID W-22 lists; (Hirsh et al., 1952)) in which the percentage of words repeated correctly constitutes the score. More recently, standardized speech-in-noise protocols have emerged, such as the Bamford-Kowal-Bench Speech in Noise Test(BKB-SIN; Bench, Kowal, & Bamford, 1979), the Quick Speech in Noise Test (QuickSIN; Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004), the Hearing in Noise Test (HINT; Nilsson, Soli, & Sullivan, 1994) and the Words in Noise Test (WIN; Wilson & Burks, 2005). In these tests, the score is the signal-to-noise ratio where a listener recognizes the speech materials correctly for a fixed percentage of the presentations (e.g., 50%).

As shown in our hypothetical example, it is often possible that two listeners could receive an identical score even though one of the listeners may find that listening in typical day-to-day situations is extremely challenging and requires great effort. Researchers involved with telephone engineering have long recognized that intelligibility testing (i.e., observing how many words are correctly reported by a listener at the other end of the line) does not differentiate in a situation where a listener may score within a region of high intelligibility but report that the voice was unintelligible and required considerable 'mental effort' to discriminate (Broadbent, 1958; Fletcher, 1953).

The challenge faced by clinicians is that on the basis of the audiogram and speech test results, listeners with equal scores may be provided with similar audiological rehabilitative services such as amplification despite the fact that there could be large differences in the amount of listening effort. We therefore argue that listening effort is an important variable to consider. Listening effort is an important dimension of speech understanding, yet much of clinical audiology remains focused on assessing hearing impairment even though a significant amount of listening, comprehending and responding involves the cognitive system (Baltes & Lindenberger, 1997; Edwards, 2007; Pichora-Fuller & Singh, 2006; Sweetow & Henderson-Sabes, 2004). Listening effort refers to the attention and cognitive resources required to understand speech (Bourland-Hicks & Tharpe, 2002; Downs, 1982). In contrast, 'ease of listening' refers to the listener's perceived difficulty of the listening situation (Bourland-Hicks & Tharpe, 2002; Feuerstein, 1992).

The influence of age on listening effort

Age is an important factor to consider in terms of an individual's ability to listen and communicate because as adults age, their sensory, perceptual and cognitive functions decline (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Pichora-Fuller & Singh, 2006; Scialfa, 2002). These declines affect the ability to understand speech, especially in noisy situations. Most normal hearing older adults perform more poorly than younger adults on speech comprehension tasks, especially in noise (CHABA, 1988). In terms of day-to-day listening, many older adults indicate that listening in noisy situations is a challenging and often exhausting experience. Although it has been speculated that older adults exert increased listening effort compared to younger adults, very few studies have actually evaluated listening effort experimentally (Larsby, Hallgren, & Lyxell, 2005; Tun, Benichov, & Wingfield, 2008).

Larsby et al. (2005) examined how different speech or speech-like background noises may interact with cognitive processes important for speech understanding in young and elderly listeners with and without hearing loss. The cognitive processes evaluated included tests from the Speech and Visual Information Processing System (SVIPS) test battery (Hallgren, Larsby, Lyxell, & Arlinger, 2001). In general, Larsby et al. (2005) found that relative to younger adults, the elderly subjects were more distracted by noise with temporal variations and were especially affected by noise with meaningful content. The components of the test battery that were most affected by these noise variations involved the non-word category of the lexical decision making test. For this test, participants were asked to judge whether a combination of three letters represented a real word or a non-word. However, despite the performance differences for the lexical test in terms of accuracy and reaction time scores, interestingly, the elderly listeners did not report a higher degree of perceived effort than younger subjects in these situations. Larsby et al. (2005) interpreted this finding as being due to the fact that the elderly are less prone to complain.

In terms of response time findings, research by Tun et al. (2008) demonstrated similar results. Using a sentence comprehension task, Tun et al. (2008) showed that older adults were slower than younger adults when processing speech at low sound intensities or when processing speech with difficult syntax. The increased response time results were then used to infer increased processing effort and difficulties for older adults though effort was never explicitly measured.

The influence of hearing impairment on listening effort

In addition to the influence of age on listening effort, hearing impairment can exacerbate difficulties with listening, particularly in noise (Hallgren et al., 2001; Hallgren, Larsby, Lyxell, & Arlinger, 2005; Larsby et al., 2005; Tun et al., 2008; Worrall & Hickson, 2003). A common complaint among people with hearing loss is the effort required to understand speech in noisy situations. Since the CHABA (1988) report, a comprehensive review of twenty experimental studies involving both normal hearing listeners and those with hearing loss was undertaken to examine the relationship between speech understanding in noise and cognitive abilities (Akeroyd, 2008). Akeroyd (2008) concluded that while hearing loss emerged as the primary factor in determining one's speech recognition ability in noise, cognition was secondary. Further, while no single cognitive test emerged across all the studies reviewed, Akeroyd found that measures of working memory were significantly correlated to speech understanding ability in noise (Akeroyd, 2008). For a further review of the effects of age on cognitive ability and hearing loss, readers are directed to Pichora-Fuller & Singh (2006).

The debilitating effects of hearing loss can be manifested as both auditory fatigue and as extra effort which is needed to listen to understand speech and to concentrate (Bourland-Hicks & Tharpe, 2002; Hétu, Riverin, Lalande, Getty, & St-Cyr, 1988; Kramer, Kapteyn, Festen, & Kuik, 1997). Hearing loss can dramatically alter one's social interactions and quality of life due to the increases in effort, stress, and the fatigue of coping (Demorest & Erdman, 1986). Stephens and Hétu (1991) have suggested that the World Health Organization's classification of auditory handicap (WHO, 1980) be extended to include the effects of effort and fatigue.

Humes (1999) examined the multidimensional nature of hearing aid outcome. In this study, principal component analyses were used to evaluate functional associations between different outcome parameters. Interestingly, the notion of "effort" emerged as a separate aspect of hearing aid outcome that was distinct from aided speech recognition performance.

Compared to normal hearing listeners, Larsby et al. (2005) found that listeners with hearing loss had more problems completing the SVIPS test battery in noises with a high degree of temporal variations (i.e., a single or multi-talker babble noise compared to a steady state noise). Collapsing the data across younger and older adults, the perceived effort ratings of listeners with hearing loss were significantly higher than the perceived effort ratings of normal hearing listeners (Larsby et al., 2005). The highest effort ratings for listeners with hearing loss were obtained for tasks that were administered in an auditory-only modality, followed by audiovisual conditions. Text-based tests required the least effort (Larsby et al., 2005).

Tun et al. (2008) used response latency data to demonstrate that older adults with hearing loss were slower than older adults with normal hearing and even younger adults with hearing loss. Subjects were asked to verify the accuracy of sentences presented at either low levels or with complex syntactic structure. While effort was not explicitly measured, these findings were used to conclude that older adults with poor hearing are slower at processing sentences under challenging conditions (e.g., low sound intensity, difficult syntax) due to increased processing effort (Tun et al., 2008).

Subjective measures of listening effort

Questionnaires

Given the importance of measuring listening effort, the question for practicing clinicians is how to obtain a reliable measure of listening effort? Currently, if listening effort is evaluated in audiological practice, it is done with self-reports or rating scales designed to measure handicap reduction, acceptance, benefit, and satisfaction with hearing-aid amplification (Humes & Humes, 2004). Two examples of questionnaires that quantify handicap due to hearing loss and measure change in perceived handicap after the fitting of hearing aids include the Hearing Handicap Inventory for Adults (HHIA; Newman, Weinstein, Jacobson, & Hug, 1991) and the Hearing Handicap Inventory for the Elderly (HHIE Weinstein, Spitzer, & Ventry, 1986). One promising new questionnaire which can be administered in an interview format is the Speech, Spatial and Qualities of Hearing Scale (SSQ; Gatehouse & Noble, 2004). The 80 questions of the SSQ are designed to measure both dynamic and static aspects of hearing function. The questionnaire includes items to assess hearing disabilities and handicap as they relate to auditory attention, perceptions of distance and movement, sound-source segregation, prosody, sound quality and listening effort. The items that specifically target listening effort include questions 14, 18 and 19 from the Qualities scale (Gatehouse & Akeroyd, 2006):

> Qualities 14: Do you have to concentrate very much when listening to someone or something?
>
> Qualities 18: Do you have to put in a lot of effort to hear what is being said in conversation with others?
>
> Qualities 19: Can you easily ignore other sounds when trying to listen to something?

In a recent study designed to determine the benefits of binaural amplification, the SSQ was used (Gatehouse & Akeroyd, 2006). In addition to the expected dynamic benefits of binaural amplification relative to monaural amplification, the SSQ was able to show a significant reduction in the effort needed to communicate effectively (Gatehouse & Akeroyd, 2006).

According to Kricos (2006), it is essential that clinicians document how successful a program of audiologic rehabilitation has been in reducing listening effort as this represents a unique aspect of hearing aid outcome which is separate from aided speech recognition. In the absence of a formalized questionnaire, Kricos suggests that an estimate of listening effort could be obtained by asking clients to rate their ease of listening on a scale from 0 to 100 with 100 representing very easy listening (Kricos, 2006).

As evidence-based practice paradigms require clinicians to demonstrate that their hearing aid fittings are providing real-world benefit, self-reports of outcome are now becoming a new standard measure for reporting treatment effectiveness, in addition to clinic-based measures of hearing aid benefit and aided speech recognition (Cox, 2003; Humes, 1999; Humes & Humes, 2004).

Acceptable Noise Level Test (ANL)

The Acceptable Noise Level Test (ANL) adds an interesting nuance to the notion of listening effort as an essential component of the test is to measure the maximum level of background noise that a listener is willing to “put up with” without becoming tired or tense while listening to a story (Nabelek, Freyaldenhoven, Tampas, Burchfield, & Muenchen, 2006; Nabelek, Tampas, & Burchfield, 2004). To obtain an ANL, a recorded story is adjusted to a listener’s most comfortable listening level (MCL). Next, background noise is increased to the maximum level that the listener will tolerate while listening to the story (i.e., the background noise level, BNL). The ANL is calculated as the difference between the two subjective measures (i.e., ANL = MCL – BNL).

The literature has reported that one’s willingness to tolerate background noise is a predictor for successful hearing aid use (Nabelek et al., 2006; Nabelek et al., 2004; Plyler, 2009). According to investigators, the ANL test can identify with 85% accuracy those individuals who will wear and use their hearing aids (Nabelek et al., 2006). Individuals that are able to “put up with” high levels of background noise (i.e., have low ANL scores) are more likely to be successful hearing aid users compared to individuals who cannot deal with background noise (i.e., have high ANL scores). ANL scores have received attention in literature because they have been shown to be reliable and consistent over time for both people with normal hearing as well as those with hearing loss (Nabelek et al., 2006; Nabelek et al., 2004; Plyler, 2009). Since ANL scores do not change with hearing aid use, it is possible that they can be measured before hearing aids are fitted and used as a predictor of hearing aid use (Nabelek et al., 2006; Nabelek et al., 2004). The unaided ANL has also been shown to be significantly related to outcome as measured by the International Outcome Inventory for Hearing Aids (IOI-HA; Taylor, 2008). However, it must be noted that the starting point of the ANL is based on two subjective level-setting measures (i.e., MCL and BNL).

Limitations of subjective measures

While self-report through questionnaires may be effective for many adult clients, several studies have shown that in the case of older adults, discrepancies exist between self-report and objective measures (Saunders & Forsline, 2006; Shulman, Pretzer-Aboff, & Anderson, 2006). Older adults tend to overestimate their capabilities and underestimate their degree of impairment (Ford et al., 1988; Uchida, Nakashima, Ando, Nino, & Shimokata, 2003).

In a similar way, the ANL test could also be underestimated by many people. Elderly people in particular may indicate a greater tolerance for speech in noise even though it may result in poorer speech comprehension. Larsby (2005) observed that the elderly are less likely to report a high degree of perceived effort than younger adults despite measurable performance differences (i.e., accuracy and response time measures). This was interpreted as evidence that the elderly are less prone to complain. This finding could also apply to the ANL. On a final note, while the ANL asks listeners to indicate when the noise is too loud, listeners are never asked any questions regarding the passage they heard. In other words, there is no actual measure of comprehension. For these reasons, an objective measure of the listening effort involved with listening comprehension would be beneficial.

The dual-task paradigm – A means to quantify listening effort

We argue that a dual-task paradigm provides a quantitative measure to assess listening effort during a specific listening condition (Bourland-Hicks & Tharpe, 2002; Broadbent, 1958). In a dual-task paradigm, participants are asked to perform two tasks (a primary and a secondary task) separately and then concurrently. To assess listening effort, the primary task typically involves a listening activity such as word recognition in quiet or in noise at a predetermined signal-to-noise (SNR) ratio. Participants are told that recognizing speech is the primary task and that any additional task is secondary. The secondary task may involve a memory task, a probe reaction time task, or a tactile pattern recognition task (Bourland-Hicks & Tharpe, 2002; Downs, 1982; Downs & Crum, 1978; Feuerstein, 1992; Fraser, Gagné, Alepins, & Dubois, 2007, 2009; Rabbitt, 1966; Rakerd, Seitz, & Whearty, 1996). Research has shown that individuals are able to prioritize one task over another based on verbal instruction (Bourland-Hicks & Tharpe, 2002; Crossley & Hiscock, 1992; Pashler, 1994; Somberg & Salthouse, 1982).

Dual-task paradigms make the implicit assumption that the cognitive system has a limited capacity of resources available at any given point in time (Kahneman, 1973). When individuals are required to divide their attention between two tasks, it is this limited processing capacity that is being tested. For the last century, psychologists have been interested in people's ability to perform two or more activities concurrently. By overloading a system, it can be determined what the parts of a system are and how they function together (Pashler, 1994). The principles from Lavie's cognitive load theory can be applied to dual task research paradigms (Lavie, 1995, 2005). Under conditions of low load, spare capacity from the primary task spills over to the secondary task, with no performance decrements to either task when they are performed in combination. However, under conditions of high load, where processing capacity is exceeded, decrements to secondary task performance will be observed when the tasks are performed together (Lavie, 1995).

With the dual-task paradigm, it is assumed that performance on the primary listening task utilizes the required mental capacity, and performance on any secondary task utilizes any spare or left-over mental capacity (Kahneman, 1973). Accordingly, any increase in effort or load associated with performing the primary task (e.g., adding noise to a listening task) leads to decreases in performance on the concurrent secondary task (Broadbent, 1958). As a result, declines in secondary task performance are interpreted as increases in listening effort (Downs, 1982).

Other assumptions of the capacity theory include: (a) a more difficult task requires more resources or mental capacity for execution, (b) dual task performance assumes that the two tasks compete for resources from a unique general-purpose structure and, (c) as one system is taxed more (e.g., the bottom-up perceptual systems), other systems (e.g., the top-down cognitive systems) have their capabilities negatively impacted (Edwards, 2007; Kahneman, 1973). For a complete review of the nature of dual-task interference, the processing resources involved in attention, and the impact of load on dual task performance, interested readers are referred to the following additional references: Lavie (1995, 2005); Pashler (1994); and Wickens (1984).

Studies in which a dual-task paradigm has been used to investigate aspects of speech understanding are summarized in Table 1. Broadbent (1958) was one of the first to advocate for more than just intelligibility scores to assess communication ability. His pioneering work demonstrated that while it was possible for listeners to maintain equal percent correct scores across various distorted listening conditions, it came at the expense of unequal amounts of effort exerted by the listener. The effort involved in listening was reflected by a reduction in efficiency for the simultaneously performed secondary task involving visual tracking (Broadbent, 1958).

In three studies, a memory test was used as the secondary task. In each case, the memory test was presented sequentially (i.e., after the primary task) rather than concurrently, as

Table 1
Literature Review

Author	Participants	Primary Task Description	Secondary Task Description	Significant Finding
Broadbent, 1958	6 NH adults	Word recognition using List 3 of the W-22 at 0, -200 Hz and -300 Hz downward transposed conditions each at 0 and 660 Hz high-pass filtering.	High speed visual tracking in which participants were required to keep a pointer on a line of contacts.	Under various conditions of distorted speech: 1) speech intelligibility scores were maintained for the primary task, and, 2) visual tracking accuracy performance decreased (especially with frequency transposition).
Rabbitt, 1966	Exp 1: 29 NH adults (19-53, M=39) Exp 2: 14 NH adults (17-25, M=23)	Word recognition in quiet and noise (i.e., +10 dB SNR)	Memory for primary task words	When noise was added, intelligibility remained high for the primary task but errors on the memory task increased.
Downs & Crum, 1978	49 NH adults (18-25)	Word recognition at 20, 35, 50 dB SL reference to each participant's PTA in quiet and at +6 dB SNR	Reaction time to respond to light probe	Reaction times to the light probe were significantly longer in the noise condition compared to the quiet condition irrespective of the sensation level.
Downs, 1982	23 adults with hearing loss (29-68, M=51) – with and without hearing aids	Speech recognition at 45 dB HL and 0 dB SNR, with and without hearing aids	Reaction time to respond to light probe	When adults with hearing loss wore their hearing aids, speech recognition was better and response time for the secondary task was significantly shorter, compared to the unaided condition.
Feuerstein, 1992	48 NH young adults (M=19) who simulated a hearing loss with an earplug	Speech recognition at 65 dB SPL and +5 SNR	Reaction time to respond to light probe	Binaural listening produced better word recognition and better ease of listening ratings. Response times to the light probe were shorter with binaural listening compared to monaural indirect listening (when noise was directed to the ear that was not plugged). Binaural and direct listening (when noise was directed to the ear with the earplug) were equivalent.
Rakerd et al., 1996	Exp 1: 8 NH young adults and 9 young adults with hearing loss Exp 2: 11 NH young adults (21-29, M=24) and 11 adults with hearing loss (52-73, M=62)	Noise listening task for 60 seconds and speech listening task for 60 seconds followed by 5 comprehension test questions, at 65 dB SPL for NH adults and at MCL for adults with hearing loss	Visually presented serial digit recall	Participants with hearing loss had more difficulty with digit memorization than NH listeners. More digits were forgotten when the memory retention interval was filled with speech compared to noise for those with NH and with hearing loss but those with hearing loss had more difficulty.
Bourland-Hicks & Tharpe, 2002	14 NH children (5-11) and 14 children with hearing loss (6-11)	Speech recognition of PBK word lists presented at 70 dBA at +20, +15, +10 SNR and quiet conditions	Reaction time to respond to light probe	Primary task performance remained over 80% for both listener groups but the response times for the secondary task were significantly longer for children with hearing loss compared to NH children.
Fraser et al., 2007	Exp 1: 30 NH young adults (18-41, M=25) Exp 2: 30 NH young adults (18-45, M=25)	Speech recognition in auditory (A) and auditory-visual (AV) modalities with speech at 57 dB SPL and noise at 68 and 76 dB SPL	Accuracy and response time to tactile pattern recognition task	Exp 1: When noise was presented at the same level in the AV condition relative to the A condition, speech accuracy improved and tactile response times decreased. Exp 2: When 10 dB more noise was added to the AV condition relative to the A condition, tactile response times slowed.
Choi et al., 2008	64 NH children (7-14)	Word recognition with PBK word lists presented at 65 root mean square (RMS) and +8 dB SNR	Visually presented serial digit recall	Regardless of instruction for which task should receive priority, significant dual-task decrements were seen for serial recall but not for word recognition. 7-8 year old children showed the greatest improvement in word recognition with the greatest decrease in serial recall.

is usually the case with dual task studies. Rabbit (1966) showed that while the addition of white noise did not affect the number of words correctly shadowed in the primary task, it did have a significant impact on the number of words that could be recalled in the secondary task. Later, Rakerd (1996) demonstrated that listeners with hearing loss were more adversely affected by noise than normal hearing listeners on a secondary task which involved digit memorization. Also, when the memory retention interval was filled with a speech passage (which required participants to listen for understanding) rather than noise, listeners with hearing loss had more difficulty with digit memorization than normal hearing listeners. In a more recent study, Choi et al. used a secondary task that involved serial digit recall (Choi, Lotto, Lewis, Hoover, & Stelmachowicz, 2008). Participants were instructed to remember sets of three or five numbers in the exact order of presentation. Primary and secondary task assignment was manipulated by instruction to investigate how young children could allocate their attention. Interestingly, regardless of which task was given priority, dual task decrements in performance were only associated with serial digit recall and not with word recognition. Choi found that children aged 7-8 years old showed the greatest improvement in word recognition but at the expense of the greatest decrease in digit recall during dual-task trials (Choi et al., 2008).

Most of the remaining studies summarized in Table 1 used a probe reaction-time test for the secondary task. This technique commonly involves the visual modality as a light signal is presented at random intervals during the primary task and the participant is required to press a button as quickly as they can to indicate that they are aware of the probe signal. Longer reaction times to the probe are associated with greater processing demands on the primary task (Downs & Crum, 1978). On the basis of this observation, Downs and Crum (1978) concluded that normal listeners required extra effort to listen in noise. Studies using this technique with people who had hearing loss found that hearing aid use can improve speech recognition and speech understanding as well as reduce listening effort (Downs, 1982). In a study by Feuerstein (1992), listeners simulated a unilateral hearing loss by inserting an earplug in one ear. The probe reaction time results indicated that binaural listening and the direct listening condition (in which noise was directed to the plugged ear) produced equivalent results. These conditions were judged to require less effort relative to the indirect listening condition (in which noise was directed to the unplugged ear). More recently, Bourland-Hicks & Tharpe (2002) demonstrated that even when children with mild to moderate or high frequency sensorineural hearing loss wore their hearing aids, they expended more effort than normal hearing children when listening in noise.

Many probe reaction time studies of listening effort also included a subjective measure of this construct. Downs and Crum (1978) incorporated a seven-point scale to indicate learning task difficulty. They found that although participants were good judges of learning accuracy, they were poor judges of how much effort was involved in the learning task. Feuerstein (1992) used a rating scale ranging from difficult (e.g., 0) to easy (e.g., 100) to indicate the perceived difficulty of the listening situation by the listener. Like Downs and Crum (1978), Feuerstein (1992) found that while ease of listening and performance accuracy on the primary speech recognition task were positively correlated, performance on the secondary response time task (i.e., listening effort) was not correlated with the subjective ease of listening measures. In a similar study, Bourland-Hicks and Tharpe (2002) asked children to rate the word-repetition task from 1 (“not hard at all”) to 5 (“very hard”). Even though the secondary task reaction time data indicated that children with hearing loss expended more effort than children with normal hearing, the two groups’ ratings of perceived effort did not differ significantly. Taken together, these studies suggest that objective and subjective measures of listening effort are not correlated in adults or children (Bourland-Hicks & Tharpe, 2002; Downs & Crum, 1978; Feuerstein, 1992). Therefore, caution is needed when measuring listening effort by subjective measures only (Bourland-Hicks & Tharpe, 2002). This further supports the case for developing an objective clinical measure of listening effort.

Of all of the studies summarized in Table 1, only one involved a non-visual and non-auditory secondary task (Fraser et al., 2007, 2009). The purpose of the study was to compare the listening effort associated with auditory vs. audiovisual speech perception in young adults. While the primary task involved closed-set sentence-recognition, the secondary task consisted of tactile or somatosensory pattern recognition. By using a secondary task unrelated to the primary tasks’ sensory modalities, Fraser et al. (2009) excluded the possibility of structural interference (i.e., overlapping demands on the same perceptual system) (Kahneman, 1973).

In the first experiment, where the same signal-to-noise (SNR) was used for both the auditory (A) and the auditory-visual (AV) modalities, adding visual speech cues improved AV speech recognition performance and listeners rated their performance as requiring less effort. In the second experiment, the level of performance to complete the speech recognition task in isolation was equated across the A and AV modalities. This was accomplished by adding 10 dB more noise to the AV vs. the A condition. With the increased noise level in the AV modality, reaction times for both tasks were slower and tactile task accuracy was poorer. Despite these performance differences, participants ratings of perceived effort did not differ between the two modalities, which again emphasizes need for an objective test of listening effort (Fraser et al., 2007, 2009).

Clinical Implications

With the current trends of population aging, it is estimated that by 2050 approximately 59% of the overall audiology caseload will consist of older adults (Worrall & Hickson, 2003). Systematic testing of dual task paradigm performance would give clinicians an additional performance index over and beyond traditional word recognition scores. In addition, the dual task paradigm provides a more ecological approach to test speech recognition performance as it is often the case that we have to process speech and perform other tasks at the same time (e.g., listen to a lecture and take notes simultaneously). An objective measure of listening effort that takes into account a listener's cognitive capacity can provide a sensitive means to differentiate listener outcomes – especially for older adults who may demonstrate equivalent hearing sensitivity and word recognition performance.

More than 50 years ago, Broadbent (1958) concluded that there was a need for multiple criteria in assessing communication channels and that more than the speech recognition scores should be used to assess communication ability. However, it has only been recently that investigators have begun to explore the relationships between cognitive ability, listening conditions and hearing aid settings. Research has demonstrated that the results from a reading span test can be used to optimize the compression settings of hearing aids (Foo, Rudner, Ronnberg, & Lunner, 2007; Gatehouse, Naylor, & Elberling, 2003, 2006; Lunner, 2003; Lunner & Sundewall-Thoren, 2007; Rudner, Foo, Ronnberg, & Lunner, 2007). Other researchers have used dual-task paradigms to evaluate the effectiveness of different noise reduction algorithms incorporated in hearing aids (Edwards, 2007; Sarampalis, Kalluri, Edwards, & Hafer, 2006, 2009). In these studies, the primary task involved either word or sentence recognition at various signal-to-noise ratios. The secondary tasks involved either holding words in short-term memory or responding to a complex visual reaction-time task in which a driving game was used to gauge the mental effort involved with speech understanding. The results of these studies suggest that noise reduction algorithms reduce listening effort and free cognitive resources for other tasks (Sarampalis et al., 2006, 2009).

To our knowledge, use of a dual-task paradigm has never been used to quantify the listening effort related to understanding speech by older adults. Clinically, the use of this approach could be beneficial because the current means of assessing listening effort involves self-report scales. Research findings have revealed discrepancies between self-report ratings by seniors and related objective or behavioural measures (Saunders & Forsline, 2006; Shulman et al., 2006). Specifically, older adults tend to overestimate their capabilities and underestimate their degree of impairment (Ford et al., 1988; Uchida et al., 2003). Taken together, this underscores the importance of developing an objective test that can be implemented clinically to evaluate listening effort.

In addition to aided speech recognition scores and measures of subjective benefit, in the future, an objective measure of listening effort or cognitive benefit could be used by clinicians (a) as an assessment tool, (b) as an outcome measure to differentiate listeners, (c) to target clients that would benefit from aural rehabilitation and (d) to optimize an individual's hearing aid settings to improve speech understanding (Humes, 1999; Humes & Humes, 2004; Sarampalis et al., 2009).

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