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Relating working memory to compression parameters in clinically-fit hearing aids

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Abstract

Purpose—Several laboratory studies have demonstrated that working memory may influence response to compression speed in controlled (i.e., laboratory) comparisons of compression. In this study, we explored whether the same relationship would occur under less controlled conditions, as might occur in a typical audiology clinic.

Method—Participants included 27 older adults who sought hearing care in a private practice audiology clinic. Working memory was measured for each participant using a reading span test. We examined the relationship between working memory and aided speech recognition in noise, using clinically-fit hearing aids with a range of compression speeds.

Results—Working memory, amount of hearing loss, and age each contributed to speech recognition but the contribution depended on the speed of the compression processor. For fast-acting compression, the best performance was obtained by patients with high working memory. For slow-acting compression, speech recognition was affected by age and amount of hearing loss but was not affected by working memory.

Conclusions—Despite the expectation of greater variability from differences in compression implementation, number of compression channels or attendant signal processing, the relationship between working memory and compression speed showed a similar pattern as results from more controlled, laboratory-based studies.

Clinical audiologists have long been aware that speech recognition varies among patients, even those with similar pure-tone audiograms. This variability comes from many sources, including differences in suprathreshold processing (e.g., Bernstein, Mehraei, et al., 2013; Bernstein, Summers, Grassi, & Grant, 2013; Grant, Walden, Summers, & Leek, 2013; Summers, Makashay, Theodoroff, & Leek, 2013) and central auditory processing (Gates, 2012). Recent models (Ronnberg et al., 2013; Ronnberg, Rudner, Foo, & Lunner, 2008; Rudner, Foo, Ronnberg, & Lunner, 2007) propose that differences in *working memory* may also contribute to variability in speech recognition. Working memory refers to the system that provides temporary storage and manipulation of the information during complex cognitive tasks (Baddeley, 1992). Ronnberg and colleagues argued that in situations where the incoming auditory information is deficient (as with hearing loss, background noise, or other distortions to the acoustic signal) the listener must rely to a greater extent on cognitive

processing to extract meaning from the signal. In those situations, listeners with low working memory may be at a disadvantage. Indeed, patients with low working memory have been shown to perform more poorly than patients with high working memory under degraded listening conditions, such as when speech is rendered less audible by hearing loss (e.g., Cervera, Soler, Dasi, & Ruiz, 2009); masked by background noise (e.g., Pichora-Fuller, Schneider, & Daneman, 1995; Lunner, 2003; Akeroyd, 2008); or when suprathreshold cues are degraded due to spectral smoothing (Schvartz, Chatterjee, & Gordon-Salant, 2008).

Working memory may also be related to listeners' response to amplification, including frequency compression (Arehart, Souza, Baca, & Kates, 2013) and digital noise reduction (Arehart, Souza, Lunner, Syskind Pedersen, & Kates, 2013; Ng, Rudner, Lunner, Pedersen, & Ronnberg, 2013). Most relevant to this paper, several studies have shown that listeners with low working memory perform poorly with fast-acting wide-dynamic range compression (WDRC) (Foo, Rudner, Ronnberg, & Lunner, 2007; Gatehouse, Naylor, & Elberling, 2006; Lunner & Sundewall-Thoren, 2007; Ohlenforst, Souza, & Macdonald, 2014). This finding has been attributed to difficulty matching an altered acoustic signal—as would occur when fast-acting WDRC alters the speech envelope (Jenstad & Souza, 2007; Jenstad & Souza, 2005)—to stored information in the lexicon (Ronnberg et al., 2013; Ronnberg et al., 2008). Following from this line of argument, we might expect patients with low working memory to perform best with slow-acting WDRC that more closely preserves the natural amplitude variations of the input speech signal.

Several issues are of interest in translation of the laboratory work to audiology practice. In studies which related working memory to compression speed, compression attack and/or release times were varied without changing other fitting parameters. Specifically, the frequency-gain response, number of compression channels, compression threshold, compression ratio and the inclusion of digital noise reduction were usually held constant across compression-speed conditions. While such experimental control is an appropriate and necessary approach to a research question, it may not closely mimic what happens in the clinic. Current commercial hearing aids rarely allow direct adjustment of attack and release times. In some products, compression time constants can only be changed in the context of a group of settings; more commonly, they are fixed within the product line. Accordingly, a clinical audiologist who desires to fit slow-acting compression is most likely to do so by selecting a manufacturer whose products have long release times. That audiologist will not only be selecting time constants but also an accompanying set of processing parameters, including the number of compression channels and any attendant signal processing. It is unclear whether release time will be related to working memory when compression speed is paired with other signal processing, such as digital noise reduction.

In addition, the earlier data relied on relatively simple processors. Most studies (Cox & Xu, 2010; Foo et al., 2007; Gatehouse, Naylor, & Elberling, 2003; Gatehouse et al., 2006; Lunner & Sundewall-Thoren, 2007; Rudner, Foo, Ronnberg, & Lunner, 2009) used a two-channel wide-dynamic range compressor, as was the standard approach in wearable aids at that time. Results may be different with higher numbers of compression channels, which can produce a variety of complex envelope modifications (Souza, Hoover, Gallun, & Brennan,

2010). A recent study (Ohlenforst et al., 2014) used a six-channel compressor, but via an earphone simulation that did not encompass some effects (such as venting) which can modify the response in wearable hearing aids (Killion & Revit, 1993). Accordingly, the goal of the present study was to determine whether the relationship between working memory and compression speed—using clinical selection and fitting procedures and validation measures that are readily available in an audiology clinic—would be consistent with results from more controlled, laboratory-based studies.

Method

Participants

Participants included 27 adults (18 females and 9 males) aged 62-100 years (mean age 82.1 years) who sought audiological treatment at a private practice. All patients seen for hearing aid evaluations in a three-month period were asked if they wished to participate in additional testing as part of the hearing aid evaluation, and all agreed. Each participant received a complete audiometric evaluation consisting of pure tone air (Figure 1) and bone condition thresholds, speech recognition (monosyllabic words at 35 dB SL), speech loudness discomfort levels, immittance (tympanograms, acoustic reflex threshold, and reflex decay) and distortion-product otoacoustic emissions. All participants had bilateral sensorineural sloping hearing loss (air-bone gaps 10 dB or less at octave frequencies between .5 and 4 kHz and normal tympanograms). For all participants, auditory reflex thresholds and otoacoustic emissions results consistent with pure-tone thresholds were interpreted as a likely cochlear site of lesion. All participants were able to read and write in English and had adequate vision to read text on a computer screen. All study procedures were reviewed and approved by the Northwestern University Institutional Review Board, and each participant completed an informed consent process. Participants were not compensated for their time.

Working Memory

Tests of working memory usually require the listener to process information (such as making a semantic judgment) while storing information for later recall. Here, a reading span test (Daneman & Carpenter, 1980; Ronnberg, Arlinger, Lyxell, & Kinnefors, 1989) was used to measure working memory. To facilitate comparisons with previous work, we deliberately chose the same test as has been used in most studies relating working memory to compression speed. In addition, the use of a reading span (rather than listening span) avoids compromising test scores due to difficulty hearing test items, or allocation of cognitive resources to listening rather than processing and storage. The test consisted of 54 five-word sentences shown on a 26-inch computer screen at the rate of one word or word combination per 0.8 seconds (e.g., “The captain”, “sailed”, “his ship”). After an entire sentence was shown, the participant was asked to determine whether the sentence made sense. That semantic decision was included to engage explicit processing. Half of the sentences made sense, and half did not (in random order). Although the semantic decision was recorded, the test developers do not recommend using it in the final score as it almost always 100% and therefore uninformative. The test included three blocks each of three, four, five, and six sentences per block (in that order). After each block, the participant was (randomly) prompted to recall either first or last words of the sentences shown. It was

expected that the words would be more difficult to recall as the number of sentences per block increased. The final score was the percentage of correctly recalled words across all sentence blocks.

Hearing Aids

During the appointment, each participant was fitted binaurally with at least three different trial pairs of receiver-in-canal hearing aids. The full test set of hearing aids spanned several different manufacturers. Manufacturer-specified attack and release times are shown in Table 1. In each case, the hearing aids selected for a particular participant represented a range of compression speeds from slow to fast. Each patient completed a within-manufacturer comparison, plus one or two across-manufacturer comparisons. The across-manufacturer comparisons reflected products that might be prescribed for the patient's needs and preferences as determined by clinician expertise. For example, the fitting audiologist considered ease of use such as larger or rechargeable batteries in cases of limited dexterity; availability of a manual volume control for patients who wanted that option; or size of aid (e.g., some larger aid cases were uncomfortable for some patients). With the exception of the within-manufacturer comparison, none of the other hearing aids allowed adjustment of compression time constants, thus all were fit with the product's default attack and release times. All of the aids employed multichannel compression, ranging from 6 to 20 channels. As would be the case in most clinics, the choice of hearing aid incorporated compression speed as one of a number of criteria. In the final data set, 17 patients were tested with three different aids and 10 patients with four different aids. The order of compression speeds was randomly selected for each patient. The same earmold (typically an appropriate-diameter closed dome) was used with all hearing aids for a particular patient.

Each hearing aid was programmed for the patient's audiogram using DSL v5.0 (Scollie et al., 2005) adult targets. The hearing aid response was verified by measuring the real ear aided response at 50 and 65 dB SPL input levels. Any necessary adjustments were made to obtain a clinically appropriate match (within 5 dB of the prescribed targets through 3 kHz). The real-ear saturation response (RESR) was measured and the maximum output was reduced if RESR exceeded the patient's LDL. As would be the case in any clinical fitting, the compression ratio and compression threshold were determined by any adjustments necessary to meet prescriptive targets. The remaining parameters (e.g., noise reduction, feedback suppression) were engaged according to the manufacturer's default parameters. For the purposes of this testing, all hearing aids were set to an omnidirectional microphone response.

Outcome measurements

For each amplification condition, a speech-in-noise threshold was obtained using the QuickSIN (Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004). The QuickSIN was selected because it was suitable for testing in a time-limited clinical environment and because it consisted of low-context sentences in a background of noise (four-talker babble) that contained modulations, so was similar to test conditions which have been shown to be sensitive to differences in compression parameters in previous work (Lunner & Sundewall-Thoren, 2007; Ohlenforst et al., 2014). The QuickSIN was delivered in soundfield at 0

degree azimuth in a single-walled test suite. Two QuickSIN lists were randomly selected for each condition. For the majority of subjects, the presentation level was 70 dB HL, in accordance with the test instructions. Seven participants had a three-frequency pure-tone average that exceeded 50 dB HL. For those participants, the presentation level was increased to a “loud but ok” value. The final score in each condition was the mean score across the two lists. An unaided QuickSIN was obtained using the same paradigm.

Results

Working memory

Individual working memory scores for the study cohort ranged from 17% to 50%, with a mean score of 34%. Table 2 shows correlations between age, amount of hearing loss (expressed as average of thresholds at .5, 1, and 2 kHz), working memory, and speech-in-noise performance. As expected, participants who were older or had worse hearing thresholds had more difficulty understanding speech in noise, both with and without amplification. Working memory was significantly correlated with aided QuickSIN scores. Within this sample, there was a tendency for lower working memory scores to occur in the older patients and also to be associated with poor unaided speech-in-noise performance, but neither relationship reached statistical significance.

Relationship between working memory and compression speed

Most previous studies have categorized patients as having either high or low working memory on the basis of the median score for the group. A similar comparison is shown in Figure 2. Larger QuickSIN values represent poorer performance, in which a more favorable SNR was required to reach threshold. For the slower compression speeds, scores overlapped for the high and low working memory groups. At faster compression speeds, patients with high working memory performed better with fast compression, and patients with low working memory with slow compression. For the fastest-acting compression ($RT < 12$ ms), the between-group difference was greater than 5 dB. This is a substantial difference for a test where 2.7 dB is considered clinically significant to a 95% confidence interval (Killion et al., 2004).

In the context of clinical application, we were interested in the relationship between individual working memory and compression speed. That relationship is plotted in Figure 3. Each panel shows results for a different compression speed. Values in the top right of each panel quantify the strength of the relationship. Aided QuickSIN scores were significantly related to working memory for the faster compression speeds, but not for the slower compression speeds. There was also considerable scatter, particularly for the slower compression speeds. This likely reflected the complex nature of speech-in-noise recognition, in which factors other than working memory played a role.

To explore those relationships, two hierarchical regression models were calculated, one for the fastest compression (Table 3) and one for the slowest compression (Table 4). Each model used an alpha-level criterion of 0.05 for probability of entry into the model and 0.10 for probability for removal from the mode. Residual and scatter plots indicated that the

assumptions of normality and linearity were satisfied. The dependent variable was speech-in-noise score. The predictors were entered sequentially, with order of entry into the model designed to examine the primary predictive variable of interest (working memory) while considering the effects of hearing loss (expressed as average of thresholds at .5, 1 and 2 kHz) and age. Recall that the independent variables were significantly correlated (Table 2). However, collinearity within the models was acceptable (VIFs <2.0, tolerances > .5).

For the fastest compression speed (hearing aid C), working memory explained 30% of the variance ($F_{1,13}=5.17, p=.042$). When hearing loss was added as a predictor, the change in variance accounted for was significant (Table 4). The contribution of working memory decreased slightly when hearing was added. That model accounted for 73% of the variance ($F_{2,13}=14.59, p=.001$). No additional variance was explained when age was added as a predictor.

For the slowest compression speed (hearing aid A), working memory only explained 8% of the variance and the overall model was not significant ($F_{1,22}=1.85, p=.188$). The variance accounted for increased significantly with the addition of hearing loss and age as predictors. The final model accounted for 63% of the variance, none of it attributed to working memory ($F_{3,22}=10.90, p<.005$).

Discussion

Working memory and compression speed

There has been considerable interest in the idea that customizing amplification parameters to the individual's working memory could improve aided speech recognition. In the present study, this issue was addressed in a scenario that mimicked the situation that will occur in non-research settings. Working memory was measured for patients undergoing routine hearing aid evaluations and fast-acting or slow-acting compression was implemented in clinically-fit wearable aids, without the narrow controls used in laboratory settings. Under those circumstances, both working memory and amount of hearing loss contributed to speech recognition scores measured with fast-acting compression. Working memory did not contribute to speech recognition scores measured with slow-acting compression. Instead, speech recognition with slow-acting compression was predicted by the amount of hearing loss and by listener age.

The pattern of results was consistent with results obtained in laboratory studies (Foo et al., 2007; Lunner, 2003; Lunner & Sundewall-Thoren, 2007; Rudner et al., 2009), which also showed a relationship between working memory and compression speed. Specifically, those studies suggested that listeners with low working memory may not perform well with fast-acting compression. The agreement with previous work is encouraging, because the data reported here were collected under more realistic but less controlled conditions. For example, although we fit all aids to the same prescriptive target and disabled microphone directionality, each aid had different numbers of compression channels and unique noise reduction and feedback settings. Even for the within-product comparison (hearing aid B), changing compression speed also changed other signal processing. Accordingly, every compression-speed comparison was confounded by processing differences that would be

present in a clinical fitting. Another difference is that our listeners were fit with relatively open earmolds resulting in a combined vent path plus amplified signal, in contrast to the closed-fitting approach that guaranteed receipt of only the compression-amplified signal in previous studies. Despite those differences, the pattern of the data supports laboratory data which used more constrained protocols. This is an encouraging finding as we begin to translate research findings into clinical practice.

One caution is that our comparison was conducted at the fitting appointment and did not allow for any acclimatization to compression. Some models of working memory suggest that the consequences of low working memory should be most noticeable for unfamiliar signals, and should diminish with long-term exposure. There is some evidence to support this hypothesis (Rudner et al., 2009). Perhaps later testing of the same patients would have shown a more or less pronounced effect. On the other hand, several studies have shown that low working memory is associated with poor response to fast compression even after weeks of hearing aid experience (Gatehouse et al., 2006; Lunner & Sundewall-Thoren, 2007). Additional work may help us to understand these effects.

Working memory measurements in older adults

It may also be of interest to comment on our experience measuring working memory in this clinical sample. Our working memory scores were about 10% lower than in previous (laboratory-based) work (Table 3). This may be due to differences in age, as our sample was about a decade older than the other samples. Previous work has consistently shown a decline in working memory with age (Salthouse, 1994), although usually over a much broader age range; for example, by comparing adults in their 20s to adults in their 60s or 70s. It is also possible that our lower scores reflect a difference between patients who volunteer for laboratory studies and a more general sample of adults who seek clinical help. The requirements of laboratory participation may cause an unintentional self-selection. Laboratory participants often must drive to a university testing facility, or attend multiple visits that are not associated with their usual health care providers. For those reasons, laboratory participants may represent adults who are actively seeking opportunities to improve their performance (Galea & Tracy, 2007), or they may be in better health than their age-typical peers. Additional data collection at other sites might help confirm whether similar distributions of working memory are found in different environments.

One caution for clinicians who consider incorporating working memory tests in their practice is that the inclusion of a working memory test based on reading sentences requires some explanation to patients. Initially, some patients reacted with surprise that the test was not a “hearing” test, the issue they sought care for. This offers an opportunity for the clinician to discuss information processing across sensory domains. Clinicians should also be prepared for the test to raise concerns about declining memory. If the patient has not discussed those concerns with their primary care provider, appropriate referrals for follow-up care can be made as needed (Remensnyder, 2012).

In addition to guiding hearing aid selection, working memory tests can also be used in a more general way during patient counseling. In our experience, patients already understand that failure to communicate in complex environments is not just a “hearing” problem. In a

recent survey (Preminger & Laplante-Levesque, 2013), a majority of patients surveyed expressed concerns that poor memory and cognition could affect communication. The inclusion of a cognitive test in the audiometric battery offers an opportunity to discuss how “hearing” (auditory thresholds) and “listening” (cognitive processing) are involved in communication. In this context, the hearing aid is not presented as solving the problem (which may lead to unrealistic expectations) but as one component in a multi-faceted solution. In our practice, we also discuss how properly fit amplification or modification of the listening environment (e.g., to reduce background noise) can reduce the burden on cognitive processing. Anecdotally, patients involved in this study reported that they were more confident in the hearing-aid recommendations provided for them because they were based on “science” rather than “guessing”. Although we doubt that “guessing” is the basis of most hearing aid recommendations, such comments offer an interesting window on how patients perceive the hearing aid selection process.

Conclusion

Laboratory-based data have identified working memory as a contributing factor to speech recognition and response to compression amplification parameters. This study explored use of such measures in a clinical environment. Our data were consistent with results from laboratory studies. Patients with lower working memory demonstrated lower speech recognition with fast-acting compression. The use of cognitive testing in a real-world setting may contribute to an evidence-based method of prescribing appropriate compression parameters, as well as to fruitful discussion with patients about the nature of communication.

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Figure 1. Solid lines show left and right ear audiograms for each participant. Thick dashed lines show mean left and right ear audiograms.

Figure 2.

Mean aided QuickSIN scores for low- (filled circles) and high-working memory patients (open triangles). Aids tested are ordered from slowest compression speed (aid A) to fastest compression speed (aid C) (see Table 1 for attack and release times). Aid B represents a within-product comparison. Error bars are $\pm$ one standard error about the mean.

Figure 3.

Aided speech recognition as a function of working memory score. Each panel shows results for a different compression speed. Values in the top right corner of each panel are the Pearson correlation coefficient representing the strength of the relationship.

Table 1

Compression parameters for tested aids.

Hearing aid	A	B-slow	B-fast	C
Release time	20 sec	1000	75	< 50 ms
Attack time	2 sec	5 ms	10 ms	< 5 ms

Table 2Relationships among non-amplification variables (Pearson r).

	Age (years)	Hearing loss (PTA for .5, 1, 2 kHz)	Working memory (% correct)	Unaided QuickSIN (dB SNR)	Aided QuickSIN (dB SNR)
Age (years)		$r=.358$ $p=.067$	$r=-.317$ $p=.107$	$r=.516^{**}$ $p=.006$	$r=.542^{**}$ $p<.005$
Hearing loss (PTA for 1, 2, 4 kHz)			$r=-.221$ $p=.268$	$r=.672^{**}$ $p<.005$	$r=.569^{**}$ $p<.005$
Working memory (% correct)				$r=-.331$ $p=.091$	$r=-.310^{**}$ $p=.003$

** Asterisks indicate relationships that were significant at $p<.05$.

Table 3

Summary of regression analysis for variables predicting speech recognition in noise for the fastest compression (hearing aid C). *F* and *p* values in this table refer to the effect of adding additional variables. *F* and *p* values for the overall models are given in the text.

	Variable	β	<i>t</i>	<i>R</i>	<i>R</i> ²	<i>R</i> ²	<i>F</i>	<i>p</i>
Step 1				.55	.30	.30	5.17	.042
	Working memory	-.55	-2.28					.042
Step 2				.85	.73	.42	17.07	.002
	Working memory	-.31	-1.83					.094
	PTA	.70	4.13					.002
Step 3				.87	.76	.03	1.32	.278
	Working memory	-.31	-1.86					.094
	PTA	.85	3.97					.003
	Age	-.24	-1.15					.278

Table 4

Summary of regression analysis for variables predicting speech recognition in noise for the slowest compression (hearing aid A). *F* and *p* values in this table refer to the effect of adding additional variables. *F* and *p* values for the overall models are given in the text.

	Variable	β	<i>t</i>	<i>R</i>	<i>R</i> ²	<i>R</i> ²	<i>F</i>	<i>p</i>
Step 1				.28	.08	.08	1.85	.188
	Working memory	-.28	-1.36					.188
Step 2				.69	.48	.40	15.44	.001
	Working memory	-.13	-.78					.447
	PTA	.65	3.93					.001
Step 3				.79	.63	.15	7.82	.011
	Working memory	-.01	-.07					.945
	PTA	.56	3.78					.001
	Age	.42	2.80					.011

Table 5

Comparison of working memory scores to previous samples that used the Reading Span Test. Rows are ordered from lowest mean age to highest mean age.

Study	Number of adults	Mean age (years)	Mean RST score (%)	RST std dev (%)
Lunner (personal communication)	173	67	42.7	16.0
(Lunner, 2003)	72	67	44.1	16.7
(Foo et al., 2007)	32	70	44.1	10.7
(Ronnberg, Rudner, & Lunner, 2011)	30	70	44.3	11.0
(Rudner et al., 2009)	32	70	44.3	10.9
(Arehart, Souza, Baca, et al., 2013)	40	72	40.4	11.9
Ohlenforst et al. (2014)	22	74	34.2	10.3
This study	27	81	34.0	9.6