

Cognition and Neurosciences

High second-language proficiency protects against the effects of reverberation on listening comprehension

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The purpose of this experiment was to investigate whether classroom reverberation influences second-language (L2) listening comprehension. Moreover, we investigated whether individual differences in baseline L2 proficiency and in working memory capacity (WMC) modulate the effect of reverberation time on L2 listening comprehension. The results showed that L2 listening comprehension decreased as reverberation time increased. Participants with higher baseline L2 proficiency were less susceptible to this effect. WMC was also related to the effect of reverberation (although just barely significant), but the effect of WMC was eliminated when baseline L2 proficiency was statistically controlled. Taken together, the results suggest that top-down cognitive capabilities support listening in adverse conditions. Potential implications for the Swedish national tests in English are discussed.

Key words: Reverberation, comprehension, speech perception, working memory capacity, second language.

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INTRODUCTION

Noise in the classroom has well-documented, negative, effects on learning (Hygge, 2003; Hygge, Evans & Bullinger, 2002; Smith, 2012; Szalma & Hancock, 2011) and various visual-verbal skills like writing (Sörqvist, Nösl & Halin, 2012), reading comprehension (Sörqvist, Halin & Hygge, 2012) and mathematical problem solving (Ljung, Sörqvist & Hygge, 2009). Background noise also impairs auditory and communication related skills like identification and memory of spoken information (Kjellberg, Ljung & Hallman, 2008; Ljung, Israelsson & Hygge, 2012). It has, for instance, been shown that classroom reverberation can impair listening comprehension (Klatte, Lachmann & Meis, 2010), memory of spoken lectures (Ljung, Sörqvist, Kjellberg & Green, 2009) and memory of spoken word lists (Ljung & Kjellberg, 2009), even when the listening conditions are within the acceptable range according to prevailing acoustical norms (Ljung *et al.*, 2009). In this paper, we address whether reverberation influences second-language (L2) listening comprehension and whether individual differences in cognitive skills modulate this effect.

Reverberation time is the time it takes for an auditory signal to drop 60 dB after the sound source has been turned off, which ultimately depends on surface structures in the environment. With reverberation, earlier parts of the spoken message bounce against the surfaces of the room (e.g., walls and ceiling) and arrive to the ear at the same time as the later parts of the spoken message. Thus, at long reverberation times, the speech signal is masked which makes it harder to comprehend (Klatte *et al.*, 2010; Klatte, Bergstroem & Lachmann, 2013). Another factor that influences speech intelligibility is semantic context and the ability to use semantic cues to interpret meaning (Weber & Cutler, 2004; Zekveld,

Rudner, Johnsrude, Dirk, Heslenfeld & Rönnerberg 2012; Zekveld, Rudner, Johnsrude, Festen, Van Beek & Rönnerberg, 2011). A third factor that influences speech intelligibility is the listener's working memory capacity (WMC). WMC is conventionally operationalized as a participant's score on a so-called complex-span task that combines mnemonic short-term memory processes with a concurrent distractor activity (Conway, Kane, Bunting, Hambrick, Wilhelm & Engle, 2005) and WMC is viewed as a roughly constant 'trait' rather than a changing 'state' (Ilkowska & Engle, 2010). It has consistently found that individual variations in WMC predict the ability to identify (Rönnerberg, Lunner, Zekveld *et al.*, 2013; Rönnerberg, Rudner, Lunner & Zekveld, 2010) and remember (Kjellberg *et al.*, 2008; Ljung *et al.*, 2012; Sörqvist & Rönnerberg, 2012) masked spoken messages. Specifically, higher WMC is typically associated with a smaller susceptibility to the effects of masking sound. A fourth factor that influences speech intelligibility is language proficiency (Kidd, Watson & Gygi, 2007; Pichora-Fuller, Schneider & Daneman, 1995; Tabri, Abou Chacra & Pring, 2011), especially when the spoken message is masked by noise (Mayo, Florentine & Buus, 1997). The ability to compensate for the information lost due to masking noise, and to comprehend a masked message that is spoken in the listener's second language (e.g., English to native Swedish speakers), depends on the listener's baseline second language skills (see also Payne, Kalibatseva & Jungers, 2009, for similar findings related to domain-specific knowledge). There may well be a trade-off between these factors (individual differences in WMC and individual differences in baseline knowledge) in the way they contribute to L2 listening comprehension under poor listening conditions. Arguably, experience – and the support from long-term memory systems – may compensate for the need of cognitively taxing interpretation processes in a working memory system.

In a recent study, Kilman, L., Zekveld, A. A., Hällgren, M. & Rönnerberg, J. (submitted) explored the role for WMC and second language proficiency in comprehension of spoken second language sentences. Specifically, Swedish speaking participants, with English as second language, were requested to listen to sentences spoken either in Swedish or in English. Moreover, the sentences were either masked by two Swedish talkers or by two English talkers. It was found that baseline English language proficiency influenced the ability to comprehend English sentences, especially when the target was masked by English talkers. Participants with higher second language proficiency were less impaired by the masking talkers. Individual differences in L2-WMC were also related to the effect of masking, but L2 proficiency was a stronger predictor of this effect (Kilman, L., Zekveld, A. A., Hällgren, M. & Rönnerberg, J. submitted). Thus, top-down factors influence the ability to comprehend speech in adverse listening conditions. Interestingly, complex-span tasks that involve processing and maintenance of second language material (i.e., a measure of L2-WMC) are strong predictors of L2 reading comprehension (e.g., Harrington & Sawyer, 1992) and perception of L2 spoken messages masked by noise (Mann, Canny, Reser & Rajan, 2013). One possibility is that L2-WMC is a particularly good predictor of L2 language skills because a complex-span task that involves L2 material not only measures the participant's WMC, but also, in addition, domain-specific L2 knowledge (i.e., $L2-WMC = L1-WMC + \text{domain-specific L2 knowledge}$).

Building on these studies, we conducted a study to test whether classroom reverberation can impair L2 listening comprehension, and, in particular, whether the effect of reverberation is modulated by individual differences in baseline English proficiency (hereinafter called baseline L2 proficiency) and in WMC. We hypothesized that a measure of L2-WMC might be a stronger predictor of the effects of reverberation on L2 listening comprehension than a measure of L1-WMC, as L2-WMC should specifically tap into second language cognitive structures necessary for L2 comprehension under adverse listening conditions.

To meet the requirements stated by the Swedish acoustic norms SS25268:2007, classroom reverberation time should be 0.8 sec in the low frequency range. However, there are many classrooms that do not meet this requirement. Sjöström (2007) performed a comprehensive series of acoustical measurements of 225 Swedish classrooms, and found that only 20% met the acoustical norms, and a few classrooms had reverberation times longer than 1.7 sec. Similarly, Ljung et al. (2009) recorded a reverberation time of 1.84 sec in the 125 Hz frequency band in a Swedish classroom. Based on these observations, we compared three reverberation time conditions: one with rather short reverberation time; one just above the recommendations; and one rather extreme, but still ecologically valid, case.

METHOD

Participants

A total of 45 participants with a mean age of 30.42 years ($SD = 7.64$) took part in the experiment in exchange for cinema tickets. All were native Swedish speakers. The participants were screened for normal hearing and all reported no reading disabilities.

Apparatus and materials

L2 listening comprehension test. Three different L2 listening comprehension tests, taken from the National Tests of English for senior Swedish high school students (http://www.nafs.gu.se/prov_engelska/exempel_pro_vuppfigter/engelska_b_exempelupp/), were administered. Each test involved listening to a conversation spoken in the listeners' second language (i.e., English) by native English speakers, presented over headphones. The three conversations/sound files ranged from approximately 13 minutes to 15.5 minutes in length. The standard administration procedure for the National Tests of English was used, with the exception that the sound was presented over headphones instead of using a loudspeaker. In response to each test, the participants answered a set of questions. The comprehension questions were printed on a paper that the participants had available from the beginning of the test. Thus, they could read and answer all the questions while listening to the conversation or during a time slot (of 15 minutes) when the conversation was at an end. The participants received one point for each accurately answered question and the total was then averaged across the total number of questions.

To simulate different room acoustic conditions, varying in reverberation time, three different rooms were designed in the sound simulation program CATT-Acoustic. The rooms were equal in shape but different in terms of reverberation time. The mean reverberation time (125 Hz to 8 kHz) for the three rooms were 0.26 sec, 0.92 sec and 1.77 sec, respectively, all measured with T_{30} . All sound files used in the present study were simulated in those three modeled rooms, the sound source was positioned in the front of the room (representing the position of the classroom lectern) and the recording position were in the back end of the room, 5.95 meters from the sound source. The Speech Transmission Index (STI) for the recordings was 0.87, 0.62 and 0.49 for the three rooms respectively.

Baseline L2 proficiency test. An English reading comprehension test was used to measure baseline L2 proficiency (Kilman, L., Zekveld, A. A., Hällgren, M. & Rönnerberg, J. submitted). Just as the L2 listening comprehension test, this reading comprehension test is part of the Swedish national test for English proficiency in senior high school students. The reading comprehension test consisted of a story, presented on half an A4-paper, and a separate paper with 12 comprehension questions. The participants had a maximum of 12 minutes to complete the task. They all had the question sheet and the story material available during the full 12 minutes.

Working memory capacity tests. The size comparison span (SICSPAN) test was used to assess L1-WMC and L2-WMC because SICSPAN is known to be a good predictor of speech processing abilities (e.g., Sörqvist & Rönnerberg, 2012). In the task used to assess L1-WMC, all words were in Swedish. And in the task used to assess L2-WMC, all words were in English. In each test, pairs of size-comparison words were presented on a computer screen (e.g., "Is HOUSE smaller than TEPEE?"). The participants were told to answer "yes" or "no" to the question by pressing a button on the keyboard, in a self-paced mode. They were urged to respond as accurately and quickly as possible. After they had pressed the button, the screen went blank and then a to-be-remembered word (e.g., CARAVAN) was presented on the screen for 800 ms. When the to-be-remembered word disappeared, either a new pair of size-comparison words was presented or the list ended, depending on the length of the list. The list length varied between two and six to-be-remembered words. There were a total of 10 lists in each WMC task (2 of each list length). All words (i.e., the size-comparison words and the to-be-remembered words) within a list were taken from the same semantic category (e.g., *Resident*: house, mansion, cave; *Vehicles*: bicycle, car, bus). No semantic category was repeated between lists and each word was presented only once during the task. Furthermore, no category was repeated across the L1-WMC and the L2-WMC tasks. The categories were counterbalanced between participants, so that the set of categories that was part of the L1-WMC task for half of the participants was part of the L2-WMC task for the other half of the participants, and vice versa. When the last word in each list had been presented, the

participants were instructed to recall as many of the to-be-remembered words as possible, in the order of presentation, by typing on the computer keyboard. Recall was self-paced. A strict serial recall criterion was used to score the task. One point was assigned to each word recalled in the accurate position, and only to those items, and the total was then averaged by the number of lists.

Design and procedure

A within-subjects design was used. Each participant sat in front of a computer monitor in groups of 7–8 participants at a time. The participants first undertook the baseline L2 proficiency test, followed by the two WMC tests (in counterbalanced order between participants), which were followed by the L2 listening comprehension tests in three reverberation time conditions (in counterbalanced order between participants). The participants received a 10 minute break after conducting the two WMC tests. In all, the experiment took approximately 90 minutes to complete.

RESULTS

Individual difference measures

Two participants evidently did not follow the task instructions and were therefore removed before the analyses. The mean score on the baseline L2 proficiency test was 9.29 ($SD = 2.56$, range 2–12). The mean score on the L1-WMC test was 6.75 ($SD = 1.84$, range 2.88–9.63) and the mean score on the L2-WMC test was 5.97 ($SD = 1.96$, range 2.52–9.49).

Second-language listening comprehension

As can be seen in Fig. 1, performance on the L2 listening comprehension test dropped as reverberation time increased. This was statistically supported by a repeated measures analysis of variance (ANOVA) with task score as dependent variable and reverberation time condition as independent variable, $F(2,88) = 27.42$, $MSE = 0.02$, $p < 0.001$, $\eta_p^2 = 0.38$. There was no significant difference between the short and the intermediate reverberation time conditions, $t(44) = 1.44$, $p = 0.16$, but the participants performed worse in the long reverberation time condition as compared with the intermediate, $t(44) = 5.35$, $p < 0.001$, and the short, $t(44) = 6.95$, $p < 0.001$, reverberation time conditions.

The relation between individual difference measures and second-language listening comprehension

The intercorrelations between scores on the L2 listening comprehension tests, the baseline L2 proficiency test and the WMC tasks are reported in Table 1. It appears as if L2-WMC is a somewhat stronger predictor of performance on the L2 listening comprehension test than L1-WMC, especially in the long reverberation time condition. Moreover, baseline L2 proficiency appears to be a strong predictor of L2 listening comprehension across all three reverberation time conditions. These results indicate that participants with high WMC and high baseline L2 proficiency are less susceptible to the effects of reverberation on L2 listening comprehension. To test this hypothesis, we used a residual analysis technique in the context of hierarchical regression analysis (Sörqvist & Rönnerberg, 2012). In these analyses,

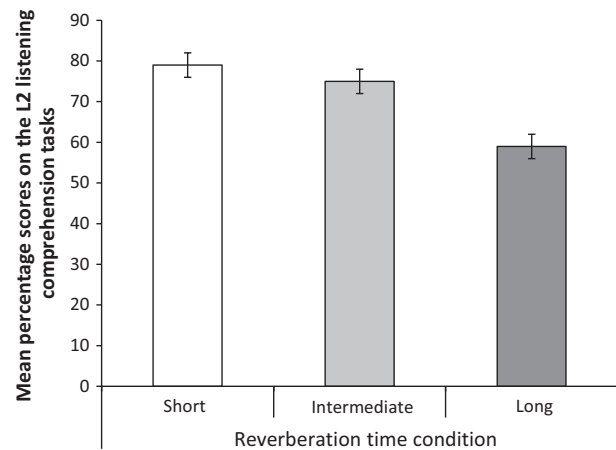


Fig. 1. The scores from Swedish speaking participants, with English as second language, on the English listening comprehension test (a part of the National Tests of English in the Swedish School System) in three reverberation time conditions (0.26 sec, 0.92 sec and 1.77 sec respectively).

L2 listening comprehension in the long reverberation time condition is the dependent variable, as we would like to know how participants differ on this variable when we have statistically considered how they differ on the independent variables. L2 listening comprehension in the short reverberation time condition is selected as independent variable in the first step of the analysis, as we wish to remove all variance in the dependent variable that can be explained by L2 listening comprehension in favorable listening conditions. The residual variance that is left to be explained in the next step of the analysis, thus, represents individual differences in the long reverberation time condition that cannot be explained by individual differences in the short reverberation time condition. If, for example, baseline L2 proficiency is significantly and positively related to this residual variance, then the results would suggest that greater baseline L2 proficiency is associated with a smaller susceptibility to the detrimental effects of reverberation on L2 listening comprehension.

In a first hierarchical regression analysis, we addressed whether the effect of reverberation on L2 listening comprehension is smaller to participants with higher L1-WMC, by adding individual differences in L1-WMC as independent variable in the second step of the analysis. L2 listening comprehension in the short reverberation time condition explained a significant part of the variance in the first step of the analysis, $\beta = 0.56$, $t = 4.47$, $p < 0.001$. Adding L1-WMC in the second step of the analysis did not explain a significant part of the variance left to be explained when L2 listening comprehension in the short reverberation time condition has been accounted for, $\Delta R = 0.001$, $\beta = 0.05$, $t = 0.34$, $p = 0.736$.

In a second hierarchical regression analysis, we addressed whether the effect of reverberation on L2 listening comprehension is smaller to participants with higher L2-WMC, by adding individual differences in L2-WMC as independent variable in the second step of the analysis. Adding L2-WMC in the second step of the analysis explained a nearly statistically significant part of the variance (6%) not explained by L2 listening comprehension in the short reverberation time condition, $\Delta R = 0.06$, $\beta = 0.26$, $t = 1.94$, $p = 0.059$. This analysis thus indicates that

Table 1. Intercorrelations between scores on the English listening comprehension tests across the three reverberation time (RevT) conditions, the baseline English proficiency test and the Swedish (L1-WMC) and English (L2-WMC) working memory capacity tasks

Measure	1	2	3	4	5
1. Listening short RevT	–				
2. Listening intermediate RevT	0.56**	–			
3. Listening long RevT	0.56**	0.52**	–		
4. Baseline English proficiency	0.58**	0.62**	0.63**	–	
5. L1-WMC	0.37*	0.37*	0.25	0.44**	–
6. L2-WMC	0.42*	0.48*	0.45*	0.62**	0.84**

Note: N = 45. * $p < 0.05$; ** $p < 0.01$.

participants with higher L2-WMC are at least slightly less susceptible to the effects of reverberation on L2 listening comprehension.

In a third hierarchical regression analysis, we addressed whether the effect of reverberation on L2 listening comprehension is smaller to participants with higher baseline L2 proficiency, by adding individual differences in baseline L2 proficiency as independent variable in the second step of the analysis. Adding baseline L2 proficiency in the second step of the analysis explained a statistically significant part of the variance (14%) not explained by L2 listening comprehension in the short reverberation time condition, $\Delta R = 0.14$, $\beta = 0.45$, $t = 3.35$, $p = 0.002$. This analysis thus indicates that participants with higher baseline L2 proficiency are less susceptible to the effects of reverberation on L2 listening comprehension. To test if this relationship persists when L2-WMC is accounted for, we added L2-WMC as an independent variable in the third step of the regression analysis. Here, L2-WMC did not explain a significant part of the variance, $\beta = 0.07$, $t = 0.50$, $p = 0.618$, but baseline L2 proficiency still explained a significant part of the variance, $\beta = 0.41$, $t = 2.53$, $p = 0.015$. In all, the detrimental effect of reverberation on L2 listening comprehension is smaller to participants who have relatively high baseline L2 proficiency (Fig. 2).

DISCUSSION

Second-language (L2) listening comprehension decreased as reverberation time increased. Participants with higher baseline L2 proficiency were less susceptible to this effect. Working memory capacity (WMC) had a similar relation to the effect of reverberation (although just barely significant) but baseline L2 proficiency was a stronger predictor.

The results reported here show that top-down cognitive factors – like WMC and language proficiency – support listening, especially in adverse listening conditions. Interestingly, L2-WMC appears to be a stronger predictor of the effect of reverberation on L2 listening comprehension than L1-WMC, just as for the effects of noise on speech perception (Mann *et al.*, 2013) and L2 reading comprehension (Harrington & Sawyer, 1992). Baseline L2 proficiency was, however, a clearly stronger predictor than L2-WMC. The effect of L2-WMC was eliminated when baseline L2 proficiency was controlled, whereas baseline L2

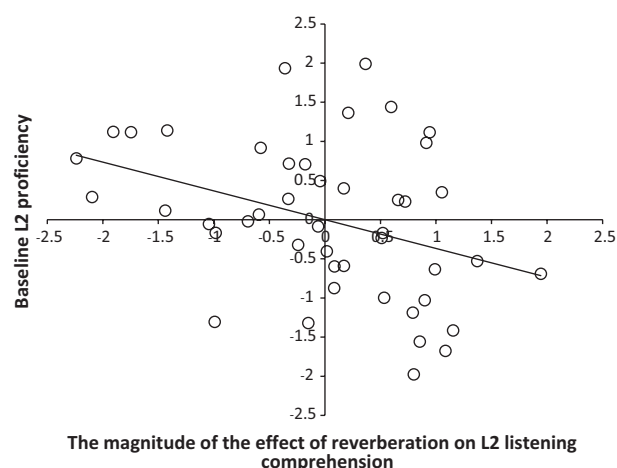


Fig. 2. The figure shows the relationship between baseline second language (L2) proficiency and the magnitude of the effect of reverberation on L2 listening comprehension (z -values). Specifically, the x-axis shows the residual scores in baseline L2 proficiency when variance explained by L2-WMC and L2 listening comprehension in the short reverberation time condition has been removed. The y-axis shows the (inverted) residual scores when variance explained by L2-WMC and L2 listening comprehension in the short reverberation time condition has been removed. The observations are inverted to better illustrate the negative relation between baseline L2 proficiency and individual differences in susceptibility to the detrimental effects of reverberation on L2 listening comprehension.

proficiency was still a significant predictor when L2-WMC was statistically controlled. How can these differences in predictive power be explained? A large body of evidence suggests that individual differences in WMC determine the efficiency by which people can search for relevant information in long-term memory (see Unsworth & Engle, 2007, for a review) and structures in long-term memory facilitate listening in adverse conditions (e.g., Johnsrude, Mackey, Hakyemez, Alexander, Trang & Carlyon, 2013). We suggest that a complex-span task that involves L2 material (and hence measures L2-WMC) is a better predictor of the effects of reverberation on L2 listening comprehension than a complex-span task that involves L1 material, because L2-WMC better reflects individual differences in the efficiency by which people can search for – and make use of – second language information stored in long-term memory (cf. Kilman, L., Zekveld, A. A., Hällgren, M. & Rönnberg, J. submitted). This is also why the baseline L2 proficiency measure is an even better predictor. L2 speech perception, and especially L2 comprehension processes, is underpinned by language structures in long-term memory that determine a person's performance on the baseline L2 proficiency measure to a greater degree than on the L2-WMC measure. In all, the ability to effectively use long-term memory information and integrate the unfolding speech signal with this information appears more relevant for speech comprehension than WMC.

It may be useful to evaluate the results reported here in view of the Ease of Language Understanding (ELU) model of speech comprehension (Rönnberg *et al.*, 2010, 2013). According to the model, speech perception runs fluently and automatically when the speech signal is unmasked (at least for native language listening). However, when the speech signal is masked, as when the room

has a long reverberation time, parts of the signal are distorted and cannot be perceived by plain bottom-up processes. In this condition, top-down cognitive factors – such as WMC and language structures – are recruited to compensate for the information loss. One finding in support of this assumption is that individual differences in WMC typically are unrelated to speech comprehension in optimal listening conditions, and thus (arguably) listening depends on bottom-up processes, whereas the comprehension processes become more and more WMC (and top-down) dependent as it becomes more difficult to identify what is said (Rönnberg *et al.*, 2010). In the current experiment, we found that WMC is related to L2 listening comprehension, even under relatively good acoustic conditions (i.e., a short reverberation time), which suggests that L2 listening is cognitively taxing (i.e., relies on top-down factors) even under good acoustic conditions, much like native listening is under poorer acoustic conditions. This is consistent with the ELU model, if it is assumed that the phonological representations in semantic long-term memory for L2 are not as firmly laid down as for the more familiar L1 representations. Hence, there should be a mismatch between signal and the phonological representation in long-term memory also in favorable acoustic conditions for L2 listening, whereby working memory is recruited to compensate for the mismatch. This would explain the correlations between WMC and L2 listening comprehension (Table 1).

The Swedish National Agency for Education – the central administrative authority for public schools in Sweden – organizes nationwide tests on a yearly basis. The students' test results are used for grading and selection purposes. Hence, it is crucial that the materials and test procedure are strictly standardized. Yet, as long as the tests are conducted in different classroom environments, this important end may not be reached. One of the tests – that is part of a larger test battery that is supposed to measure second language proficiency – is *English listening comprehension*. In this test, the students listen to spoken conversations that are played back through loudspeakers, typically stationed at the front end of the classroom. The results reported here could potentially suggest that this circumstance could lead to a situation wherein the students are, in fact, not taking the test under equal premises. The lack of a significant difference between the short (0.26 sec) and intermediate (0.92 sec) reverberation time conditions may propose that the influence from reverberation is negligible as long as it stays within a relatively normal range. However, the current study enrolled adults as participants and they had a relatively high overall score on the baseline L2 proficiency test. This circumstance should have underestimated the effect of reverberation on the national test of English listening comprehension as undertaken by younger students (e.g., regular students at the upper secondary school), as the students presumably have a lower baseline L2 proficiency level overall than older individuals. As children and adolescents are more susceptible to the effects of reverberation on speech perception than adults (Klatte *et al.*, 2010, 2013), and individual differences in language proficiency modulate susceptibility to this effect as shown here, upper secondary school students may suffer from relatively short reverberation time when undertaking a L2 listening comprehension test. In short, the results reported here indicates that school children, who are poor at L2 listening comprehension in comparison with their peers, and who may just barely get an acceptable

grade under optimal listening conditions, are those who will fail the test under more suboptimal listening conditions (i.e., a longer reverberation time) whereas those who would easily acquire a high grade under optimal listening conditions are less impaired by the suboptimal listening conditions.

Our results may suggest that poor learners (who may just barely pass the test and acquire an acceptable grade under optimal listening conditions) appear to be especially disadvantaged by a long reverberation time. With these results in mind, it is not far-fetched to raise the following question: Is the current procedure for the national English listening comprehension test fair for grade setting and selection to higher education? Since the listening test is based on recorded sound files that are played back by stereo equipment, the listener has to rely solely on the speech signal, no other cues (gestures, body language, lip reading, etc.) are available. This circumstance makes the classroom acoustics particularly potent. We suggest that, at the very least, the classrooms, where the national English listening comprehension test is administered, should live up to the national acoustic standards, or the test procedure for the national test should be changed so that differences in classroom acoustics become negligible. One way would be to allow all students to listen to the speech signal through headphones. Another possibility could be to mount a sound system solution with embedded speakers in the absorbing ceiling that includes a hearing loop amplifier. This way, it would matter less if the test is conducted in a large or a small room and the distance between the sound source and the receiver would be less crucial.

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