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Journal:	*BMJ Open*
Manuscript ID:	bmjopen-2012-002394
Article Type:	Research
Date Submitted by the Author:	22-Nov-2012
Complete List of Authors:	McShefferty, David; MRC Institute of Hearing Research (Scottish section), Whitmer, William; MRC Institute of Hearing Research (Scottish section), Swan, Iain; University of Glasgow Akeroyd, Michael; MRC Institute of Hearing Research (Scottish section),
Primary Subject Heading:	Diagnostics
Secondary Subject Heading:	Medical education and training
Keywords:	Sensitivity, Specificity, Hearing Tests

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Title page:

The effect of experience on the sensitivity and specificity of the whispered voice test: A diagnostic accuracy study

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Keywords: Sensitivity; specificity; Hearing Tests

Word count = 3794

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ABSTRACT

Objectives: To determine the sensitivity and specificity of the whispered voice test (WVT) in detecting hearing loss when administered by practitioners with different levels of experience.

Design: Diagnostic accuracy study of the WVT, through acoustic analysis of whispers of experienced and inexperienced practitioners (experiment 1) and behavioural validation of these recordings (experiment 2).

Setting: Research institute with a pool of patients sourced from local clinics in the Greater Glasgow area.

Participants: 22 people had their whispers recorded and analysed in experiment 1; 4 older experienced (OE), 4 older inexperienced (OI), and 14 younger inexperienced (YI). In experiment 2, 73 people (112 individual ears) took part in a digit recognition task using 2 OE and 2 YI whisperers from experiment 1.

Main outcome measures: Average level (dB SPL) across frequency, average level across all utterances (dB A), and within/across-digit deviation (dB A) for experiment 1. Sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) of the WVT for experiment 2.

Results: In experiment 1, OE whisperers were 8-10 dB more intense than inexperienced whisperers across all whispered utterances. Variability was low and comparable regardless of age or experience. In experiment 2, at an optimum threshold of 40 dB HL sensitivity and specificity were 63% (95% CI of 58% to 68%) and 93% (92% to 94%), respectively, for OE whisperers. PPV was 56% (51% to 61%), NPV was 95% (94% to 96%). For YI whisperers at an optimum threshold of 29 dB HL, sensitivity and specificity were 80% (78% to 82%) and 52% (50% to 55%). PPV was 65% (63% to 67%), NPV was 70% (67% to 72%).

Conclusions:

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The WVT is an effective screening test, providing the level of the whisperer is considered when setting the test's hearing-loss criterion. Possible implications are voice measurement while training for inexperienced whisperers.

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ARTICLE SUMMARY

Article focus

- Practitioners experienced in administering the whispered voice test have previously shown high sensitivity and specificity.
- There is a lack of research in the literature on the diagnostic accuracy of the test when it is administered by inexperienced practitioners.
- This study investigates the effect of experience on the diagnostic accuracy of the whispered voice test. How well do the recorded whispers of experienced and inexperienced practitioners screen for hearing loss?

Key messages

- For a given whisperer, variability in level across sessions and digits remains comparatively low and was not dependant on experience.
- Across all recorded digits, experienced whisperers were 8-10 dB greater in level than inexperienced whisperers.
- The level of the whisperer affects the test's performance, particularly if the whisperer is inexperienced.

Strengths and limitations

- The study provides both an acoustic analysis and behavioural validation of the whispered voice test.
- We used a closed set of responses, the digits 1-9, omitting letters and words sometimes used in the test.

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The effect of experience on the sensitivity and specificity of the whispered voice test: A diagnostic accuracy study

INTRODUCTION

The Whispered Voice Test (WVT) is an efficient screening test for detecting hearing loss. A tester stands behind and to the side of the patient, at arm's length from the patient's non-test ear, and whispers sets of either three digits or a combination of digits and letters. If the patient cannot repeat back over 50% of the test items over a minimum of two sets they are assumed to have an impairment worthy of full audiometric assessment.[1] The WVT has high sensitivity and specificity for adults if administered by an experienced practitioner,[2-5] though with less success in children.[6] The test has been used in large scale trials of approximately 15000 people[7] and is continually recommended clinically as a simple test of hearing ability.[8] It is the only test of hearing that requires no equipment at all. It would therefore be particularly valuable in situations where resources are limited.

A potential problem with the WVT is the whispers are spoken live, not pre-recorded. Random intensity differences may therefore occur which could affect the test results.[9] In addition, there are some other common disadvantages to free-field voice tests[10]: the failure to standardize the technique used, the inability to control the pitch of a whisper, the lack of control of background noise and the different acoustic properties of test environments. A review examining the accuracy of the WVT indicated that the problems of variations in technique and intensity are particularly relevant.[11] Only one study has quantified the variability in acoustic intensity of a set of English spoken digits, letters and words in a variant of the WVT used by the US Federal Highway Administration.[12] It found that this variant was not being administered as specified and showed high variability in the sound pressure level (SPL) of whispers, both between stimuli and between whisperers.

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Currently, no data exist on the level of training or experience necessary to achieve high sensitivity and specificity values from the WVT. The only data available where the WVT was validated by pure tone audiometry is that conducted by specialised professionals e.g. otolaryngologists, geriatricians or audiologists with previous experience of the test. There is one large-scale study which used trained practice nurses to administer the test, but it did not include an audiometric assessment to validate the results, nor was the amount or nature of the training specified.[7] If experience *does* affect the sensitivity and specificity of the WVT then a substantial proportion of patients may be incorrectly diagnosed. This is important both ways: a patient classed as normal-hearing when in fact they are impaired will not be referred for audiometric assessment, which may lead to social isolation, reduced quality of life and other associated health problems,[13] whereas a patient incorrectly classed as hearing-impaired would lead to a costly and unnecessary referral to an audiology department.

The present study evaluated the diagnostic accuracy of the WVT when administered by experienced and inexperienced practitioners, using both acoustic analyses and behavioural validation. The importance is that if experience does *not* affect the sensitivity and specificity, then the WVT could become a more viable screening tool, especially in resource- or equipment-limited situations where a simple, fast test of hearing is needed.

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METHODS

Experiment 1 – Acoustic analysis of whispered digits

The whispers of three groups of individuals were recorded and subject to acoustic analysis. The purpose was to quantify the variation in level of the whispers, across digits, person, and day.

Design and setting

The acoustic analysis employed three study groups: (1) an older experienced (OE) group, to establish the variability of professionals experienced in performing the WVT, (2) an intermediary group of older inexperienced (OI) whisperers, to determine if age was a factor in any acoustic differences, and (3) a larger, younger inexperienced (YI) group, to assess the variability of inexperienced whispers (we were unable to locate people for a potential fourth group, younger but experienced practitioners). The experiments were conducted at the Scottish Section of the MRC Institute of Hearing Research (IHR), located within Glasgow Royal Infirmary (GRI), UK.

Study population

Participants from all three groups were recruited between August 2011 and February 2012. On their initial visit each participant filled in a questionnaire relating to their first language, ethnicity and experience of the WVT. The OE group consisted of four otolaryngologists (all male, age range 50-70 years) recruited from the GRI ENT department (1 retired). Two were the authors of the original WVT paper. All were native speakers of British English. The OI group consisted of four older males (age range 41-51 years; 1 US English speaker and 3 British English speakers), with no experience of the WVT, who were recruited later from the IHR to determine if age was a factor in the intensity of whispers. The YI group was comprised of 14 inexperienced young adults (7 male, 7 female, and age range 22-31 years) recruited from the University of Glasgow School of Medicine and IHR: 11

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British English speakers, 1 Singaporean with English as a first language, 1 Italian and 1 Belgian with Italian and French as their first language respectively.

The inclusion criterion for the OE group was that they had used the WVT professionally. The inclusion criteria for both OI and YI groups were that they had *not* received training and had *not* used the test professionally or in their medical or scientific studies. An additional inclusion criterion for the OI group only was that their mean age was between that of the OE and YI groups. The exclusion criteria for all groups were if they currently smoked or if they had suffered voice strain in the last two weeks; neither of these criteria led to any exclusions.

Test methods

An acoustic mannequin (Bruel & Kjaer Head and Torso Simulator, type 4100-D) was mounted on a tripod placed inside a sound-proofed audiometric booth and connected to an amplifier (Bruel & Kjaer Sound Quality Conditioning Amplifier, type 2672). The output of the amplifier was routed to a DAT recorder (Marantz PMD690/W1B) operating at a 16-bit, 48 kHz sampling rate. To ensure levels were consistent across multiple sessions, at the start of each session the ears of the mannequin were temporarily removed and a Bruel & Kjaer Calibrator (type 4230) placed over the microphones to record 1 kHz calibration tones at 94 dB SPL.

The stimuli were the digits 1-9. We omitted the letters of the alphabet, even though sometimes included in the WVT, in order to reduce recording and editing times. For each participant in each session a list was produced containing six rows of the digits 1-9. The first row was labelled ‘conversational level’: participants were asked to say the nine digits using their normal conversational voice as a warm up. The remaining five rows were labelled ‘exhaled whisper level’: participants were instructed to exhale fully before uttering each of these digits. The position of the digits in each row was randomized using Fisher’s complete

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sets of orthogonal Latin squares and arranged in triplets.[14] The lists were displayed directly ahead of the participants, who were instructed to position themselves relative to the mannequin by placing their left hand on the mannequin's left tragus. With their left arm outstretched to maintain the appropriate distance of approximately 0.6 m they stood behind and slightly to the right of the mannequin's right ear (the recorded ear). Three sessions were recorded over three different days for each participant, giving 15 utterances of each whispered digit. The duration between each participant's recordings ranged from one day up to three weeks.

All recordings were edited in Adobe Audition 2.0 (Adobe Systems Inc.). A preset high-pass filter with a cut-off of 100 Hz was applied to reduce any mains or equipment hum before each digit was isolated and saved. All further processing was performed in Matlab (version 7.0.4, The Mathworks Inc.). Levels were computed in ⅓ octave bands from 100 to 8000 Hz, weighted by the standard "A"-weighting filter. All recordings and editing were conducted by one of the authors (DM).

The outcome measures for experiment 1 were average level across frequency bands (dB SPL), average level across all whispered utterances (dB A), within digit deviation (dB A) and across digit deviation (dB A). For all outcome measures the mean value of the OE group was used as the reference standard, the rationale being that two of the four OE whisperers had shown high sensitivity and specificity values in previously published studies.

Experiment 2 – Digit recognition task

The recordings of two OE whisperers and the least-variable YI male and female whisperers were presented to the participants in a digit recognition task analogous to the WVT. The purpose was to quantify experimentally the effect of the differences in the two groups of whisperers, using typical pure tone audiometry as the reference test.

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Study population

Participants were recruited from the available pool of patients at IHR. At the time of their invitation, no details of their hearing ability were known. The reference test was a pure-tone audiometric assessment conducted immediately before the digit recognition task.[15] All participants were treated as two single, individual ears. Inclusion followed successful completion of the audiogram, with a three-frequency (0.5, 1 & 2 kHz) pure-tone average threshold of less than 65 dB HL in the ear to be tested. A short pilot experiment had shown that participants with a threshold greater than this generally could not perform the task so any ear with this level of impairment was excluded from the digit recognition task (n = 34 ears) to avoid undue stress.

Sample size

Based on results from previous studies using a similar population, where the prevalence of hearing impairment >30 dB HL was 43%, we anticipated that clinicians would expect at least 86% sensitivity and 90% specificity.[1-2] We calculated that to obtain an estimate of sensitivity and specificity within ±10% of the anticipated values (i.e., to have 95% confidence intervals equal or less than 10% around those values), we required 108 individual ears.[16] In total 112 ears were tested.

Test methods

After a reference audiogram, participants were seated in the audiometric booth wearing headphones (AKG 720). The time interval between audiometric testing and the experimental run was at most a few minutes, being the time taken to explain the task. The stimuli were presented via PC, sound card and amplifier (Arcam A80) to the headphones. If applicable, the order of testing left and right ears was randomised. For the four whisperers chosen, all five runs from each of the three sessions were used giving 60 trials per ear. The order of trials was

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randomised for each participant, and all digits presented in a trial were from the same whisperer, session and run.

First, a practice trial was given using the most-intense conversational-level recordings of one otolaryngologist. Each trial consisted of at least two sequences of three digits, presented at a duty cycle of 0.8 seconds per digit. The digits were randomly chosen each time. After the first sequence a keypad was presented to the listener on a touch screen. Participants responded by entering the digits they heard and were presented with the second sequence. If after their second response they had scored <50% the trial was a fail. If they scored >50% the trial was a pass. If they had scored 50% they were presented with the final three digits from the set of nine. The total score was then calculated across all nine digits, again with a >50% correct requirement for a pass.

The stimuli were the recordings of the whispers made in experiment 1 from either two members of the OE group (as two previous studies using their whispered voices showed high sensitivity and specificity values) or the *least-variable* YI male and female whisperers. Onset and offset gates (5 ms) were applied to each digit to reduce any editing artefacts. To overcome the unrealistic nature of listening in a sound-proofed booth, a 2.6 s portion of a recording of the background noise of a typical ENT clinic room was randomly selected and presented simultaneously.

One audiologist or one of two research assistants administered the reference audiogram and the digit recognition task. All were trained and experienced in doing so. They were not blinded to the results of either test but had no control over the level of the whispers delivered by headphones - as it was controlled by a pre-written computer program - so they could not influence the digit recognition task. Two of the authors (DM, WW) analysed the results. The sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) of the WVT at various levels of hearing loss were calculated for both the OE

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and YI stimuli. The continuity-corrected Wilson score method was used to calculate 95% confidence intervals. [17-18]

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RESULTS

Experiment 1

Figure 1 shows the results of the ⅓-octave analysis of the whispers. Each individual digit has a distinct spectrum, as would be expected from many studies of speech. Across all whispered digits the mean level of the OE group (black line) was approximately 8-10 dB greater than the means of both other groups (blue, red lines) -- see also Table 1. These mean differences between the experienced and inexperienced groups were statistically significant [$F(2, 171) = 75.4$, $p < 0.001$]. While individual differences in level were substantial, the within-whisperer variability across groups was similar. This indicated that experience affected the overall whisper level, but neither experience nor age affected the variability of whisper levels. Within-digit variability was low for all groups, at 2-3 dB. Across-digit variability was higher for all groups, at 5-6 dB, though the mean values for OE and YI groups were comparable. Note that some degree of acoustic masking could be expected from the clinic room noise (green line), particularly at frequencies below 500 Hz.

Insert Figure 1 about here

Group	OE	OI	YI
Mean *L* (dB A) across all digits	**54** (50 to 58)*	**46** (39 to 53)	**44** (42 to 47)
Mean σ (dB A) within digits	**2.0** (1.8 to 2.2)	**2.7** (2.3 to 3.0)	**2.8** (2.6 to 2.9)
Mean σ (dB A) across digits	**5.4** (4.1 to 6.8)	**6.2** (4.8 to 7.7)	**5.5** (5.0 to 6.0)

Table 1. Summary statistics for all groups showing 95% confidence intervals (*). Mean level (L, dB A) across all digits. Mean deviation (σ, dB A) within digits i.e. the mean of the mean deviation of each individual digit in the range 1-9. Mean deviation (σ, dB A) across digits i.e. the mean deviation across the full range of 1-9. All mean values reported are averaged across all whisperers in each group for all 3 sessions.

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Experiment 2

Seventy-three participants were recruited between April 2012 and June 2012: 42 males (mean age 63.2 years, range 32 to 73 years) and 31 females (mean age 62.1 years, range 35 to 73 years). From the total of 146 ears, 112 individual ears were tested and 34 ears were excluded from testing after an audiogram due to the level of impairment being ≥ 65 dB HL (figure 2). The three-frequency (0.5, 1 & 2 kHz) PTA values of the ears tested ranged from 8 to 63 dB HL. The mean 3F PTA across all ears tested in experiment 2 was 29 dB HL (SD 10.5 dB HL). Assuming a hearing-impairment criterion of 30 dB HL, 59 of the 112 ears (53%) exceeded this criterion.

Insert Figure 2 about here

Figure 3 shows the results of the digit-recognition task using OE and YI whisperers. Each data point represents the mean percent correct over 15 trials using one whisperer as a function of each participant's 3F PTA. Data points above the 50% threshold indicate a pass. It can be seen that the spread of the data depends upon the experience of the whisperer: both OE whisperers exhibit a clear cut-off of passes vs. fails around 40 dB HL while both YI whisperers show a lower, less clear cut-off around 30 dB HL. For YI whisperers, a substantial number of participants failed to achieve over 50% correct even when their 3F PTA was below 30 dB HL. As would be expected, performance of the participants reduced with increasing 3F PTA.

Insert Figure 3 about here

From these behavioural results, a receiver operating characteristic (ROC) analysis was performed (IBM SPSS v.19) to provide a summary statistic of the accuracy of the WVT (see Figure 4). The area under the curve (AUC) represents the ability of the test to correctly classify those who have passed and failed the test. OE1 AUC was 0.916 (95% confidence interval 0.897 to 0.935), OE2 AUC was 0.896 (0.873 to 0.918). YI1 AUC was 0.732 (0.706

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to 0.757), YI2 AUC was 0.709 (0.683 to 0.734) For both OE and YI whisperers the test outcome was greater than chance but the OE whisperers would be expected to correctly classify approximately 20% more cases than the YI whisperers.

Insert Figure 4 about here

In order to identify the optimum threshold for discrimination of hearing loss we computed the d-prime (*d'*), the distance from the diagonal in an ROC curve over a range of criteria values for hearing impairment (10-50 dB HL in 1 dB increments). To avoid cases in which sensitivity and specificity were high, producing large *d'* values, but the positive predictive and negative predictive values (PPV and NPV, respectively) were low, we chose to limit optimal thresholds to those where all four diagnostic measures were greater than 50%. Using this criterion, the optimum pass/fail criterion occurred at 3F PTA of 40 dB HL for the OE group and at 29 dB HL for the YI group (Table 2). We also computed the Matthews correlation coefficient (MCC),[19] another single indicator of reliability, for the same range of sensitivity and specificity values as a further corroboration. The maximum MCC, indicating optimum discrimination, occurred at a 3F PTA of 38 dB HL for the OE group and 29 dB HL for the YI group. The MCC results were nearly identical to the optimal threshold determined by *d'*; since the sensitivity for the OE results at 38 dB HL was less than 50%, we chose 40 dB HL as the optimum threshold for that dataset. The sensitivity, specificity, PPV, NPV, accuracy and MCC for OE and YI whisperers with thresholds of 29 and 40 dB HL are shown in table 2. The OE results at 40 dB HL showed much higher accuracy than the YI results at 29 dB HL (23%), comparable to the respective difference in AUC found in the ROC analysis (Figure 4). The OE whisperers also showed dramatically higher specificity than YI whisperers, though lower sensitivity.

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(3F PTA) dB HL	Group	Sens	Spec	PPV	NPV	Accuracy	MCC
29	OE	23 (21 to 25)	98 (97 to 99)	93 (90 to 95)	53 (52 to 55)	59	0.31
	YI	**80 (78 to 82)**	**52 (50 to 55)**	**65 (63 to 67)**	**70 (67 to 72)**	**67**	**0.33**
40	**OE**	**63 (58 to 68)**	**93 (92 to 94)**	**56 (51 to 61)**	**95 (94 to 96)**	**90**	**0.54**
	YI	87 (83 to 90)	38 (37 to 40)	16 (14 to 17)	96 (94 to 97)	44	0.17

Table 2. Sensitivity, specificity, positive and negative predictive values (PPV and NPV, respectively) and accuracy (all as percentages) as well as Matthew's correlation coefficient (MCC) for OE and YI whisperers at two levels of hearing loss, 29 and 40 dB HL (3F PTA). The 95% confidence intervals shown in parentheses for sensitivity, specificity, PPV and NPV were obtained using the continuity-corrected Wilson score method.

While we used the 3F PTA values to classify hearing impairment in participants to comply with previous studies,[1-3] hearing impairment is also classified using a four-frequency average (4F PTA) of 0.5, 1, 2 and 4 kHz. We therefore repeated the analysis using 4F PTA values for comparison to 3F PTA results. Optimal thresholds increased slightly to 30 and 43 dB HL for YI and OE whisperers, respectively (Table 3). For OE whisperers the accuracy of the test was unchanged at the 43 dB HL threshold (90%), while at the 30 dB threshold the accuracy of the test was reduced from 59% to 47%. For YI whisperers at the 43 dB threshold the accuracy of the test increased from 44% to 54% and at the 30 dB threshold accuracy increased from 67% to 75%. At their respective optimal thresholds, both OE and YI whisperers had large increases in PPV and small reductions in NPV. Specificity increased from 52% to 65% for YI whisperers while sensitivity was unchanged. A small increase in specificity (93% to 98%) and a small reduction in sensitivity (63% to 56%) occurred for OE whisperers. Small increases in MCC value occurred for both groups at their optimal thresholds.

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(4F PTA) dB HL	Group	Sens	Spec	PPV	NPV	Accuracy	MCC
30	OE	19 (18 to 21)	100 (99 to 100)	99 (97 to 100)	40 (38 to 42)	47	0.27
	YI	**80 (78 to 81)**	**65 (62 to 68)**	**81 (79 to 83)**	**63 (60 to 66)**	**75**	**0.44**
43	**OE**	**56 (52 to 60)**	**98 (97 to 99)**	**88 (84 to 90)**	**90 (89 to 91)**	**90**	**0.65**
	YI	97 (95 to 98)	44 (42 to 46)	30 (28 to 32)	98 (97 to 99)	54	0.34

Table 3. Sensitivity, specificity, positive and negative predictive values (PPV and NPV, respectively) and accuracy (all as percentages) as well as Matthew's correlation coefficient (MCC) for OE and YI whisperers at two levels of hearing loss, 30 and 43 dB HL (4F PTA). The 95% confidence intervals shown in parentheses for sensitivity, specificity, PPV and NPV were obtained using the continuity-corrected Wilson score method.

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DISCUSSION

Statement of principal findings

The acoustic data demonstrate that the whispers from experienced practitioners of the WVT were on average 8-10 dB greater in level than whispers from those without experience. The variability in level, both within and across digits, and across sessions, was not dependant on experience. But the overall level differences across groups are a concern to those performing the WVT, as they lead to differences in the performance of the test. The sensitivity and specificity values for the test were highest at different levels of impairment for different groups of whisperers: 29 dB HL for YI whisperers and 40 dB HL for OE whisperers. The ROC analysis suggests the WVT is an 'excellent' test for experienced whisperers but only an 'acceptable' test for inexperienced whisperers.[20]

Strengths and weaknesses of the study

A strength of this study is that it provides both an acoustic analysis and behavioural validation of the WVT. The acoustic analysis showed clear level differences based on experience with the test. The behavioural validation showed clear differences in the optimal threshold of the WVT based on the tester's experience. Another strength of this study was that both the older experienced whisperers used in experiment 2 were the authors of two previous studies of the WVT.[1-2] There they reported that the majority of those with ≤30 dB HL could hear a whispered voice at a distance of 60 cm while the majority of those with ≥30 dB HL threshold could not.

A potential weakness is that the increased threshold of 40 dB HL for the experienced whisperers in this study may be due to differences between our laboratory validation and clinical practice (e.g. pre-recorded stimuli delivered via headphones, and a closed set of responses). Unlike the clinical testing where a patient is not given any indication of what is being whispered, participants in this study were given a closed set of responses (i.e. the digits

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1-9), potentially inflating their results. Another weakness of the current study is that other potential tokens were not tested, such as letters or words. This decision was made due to experimental time constraints. Nevertheless, we doubt that the acoustics of the whispering of single letters or words would be so different to the whispering of single digits that the results would be affected substantially. Despite these potential weaknesses, our results do show that experience does affect the sensitivity, specificity and overall accuracy of the WVT.

Meaning of the study: Possible mechanisms and implications for policy makers

This study raises the question of training in the use of the WVT. The study by Smeeth et al. used trained practice nurses,[7] but the amount of training and experience was unspecified. It is also not clear whether the majority of those who regularly administer the test have ever measured their whispered voice level, and if so, in what setting. It is obviously impractical to measure voice level before administering the test in common practice, however we believe training in the WVT should include voice level measurement. We therefore do not recommend that the WVT be administered by an inexperienced practitioner who does not know the acoustic level of their whispers.

Unanswered questions and future research

We classified whisperers into two groups, experienced and inexperienced. It would be useful to extend this to a continuous dimension of experience rather than a binary classification.

Despite its drawbacks, the WVT remains the only test of hearing that needs no equipment and can therefore be used in many circumstances where other hearing tests would be unwelcome. Further investigation and refinement of the test would be valuable. It would be of particular interest to know (1) if people can be trained to reliably produce whispers at a given – not their innate – level, (2) how the level of whispers depends on whether they are

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made before or after exhaling, and (3) how using more than one *trained* whisperer in the test affects the sensitivity and specificity.

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Acknowledgements: We thank all participants from both experiments; Patrick Howell, Neil Kirk and Kay Foreman for collecting the data; Oliver Zobay for his statistical advice; and Professor George Browning for his advice and assistance with this study.

Contributors: WW and DM participated in the study design, supervised recruitment of participants and analysed the data. All authors drafted the manuscript and/or contributed to its revision, and approved the final version. DM is guarantor.

Funding: The Scottish section of the IHR is supported by intramural funding from the Medical Research Council (grant number U135097131) and the Chief Scientist Office of the Scottish Government.

Competing interests: All authors have completed the Unified Competing interest form at www.icmje.org/coi_disclosure.pdf (available on request from the corresponding author) and declare: no financial relationships with any organisations that might have an interest in the submitted work in the previous three years; no other relationships or activities that could appear to have influenced the submitted work.

Ethical approval: This study was approved by the West of Scotland research ethics service (WoS REC(4) 09/S0704/12). All participants gave informed consent.

Data sharing: No additional data available.

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Figure Legends:

Figure 1. Average level (dB SPL) for each digit across three sessions as a function of frequency for three whisperer groups (OE, OI & YI) showing ± 1 standard deviation. Clinic room noise superimposed to show possible masking effects.

Figure 2. Flow of participants through experiment 2.

Figure 3. Mean percent correct over 15 simulated whispered voice test trials as a function of three-frequency pure-tone average (PTA) hearing loss for 112 individual ears tested with the recordings of 2 OE and 2 YI whisperers. Data points above the 50% threshold indicate a pass.

Figure 4. ROC analysis for experienced and inexperienced whisperers, showing sensitivity as a function of false positive rate for each whisperer (separate panels). Points along the curve are labelled in 5 dB HL increments, and the total area under the curve (AUC) is given below the diagonal.

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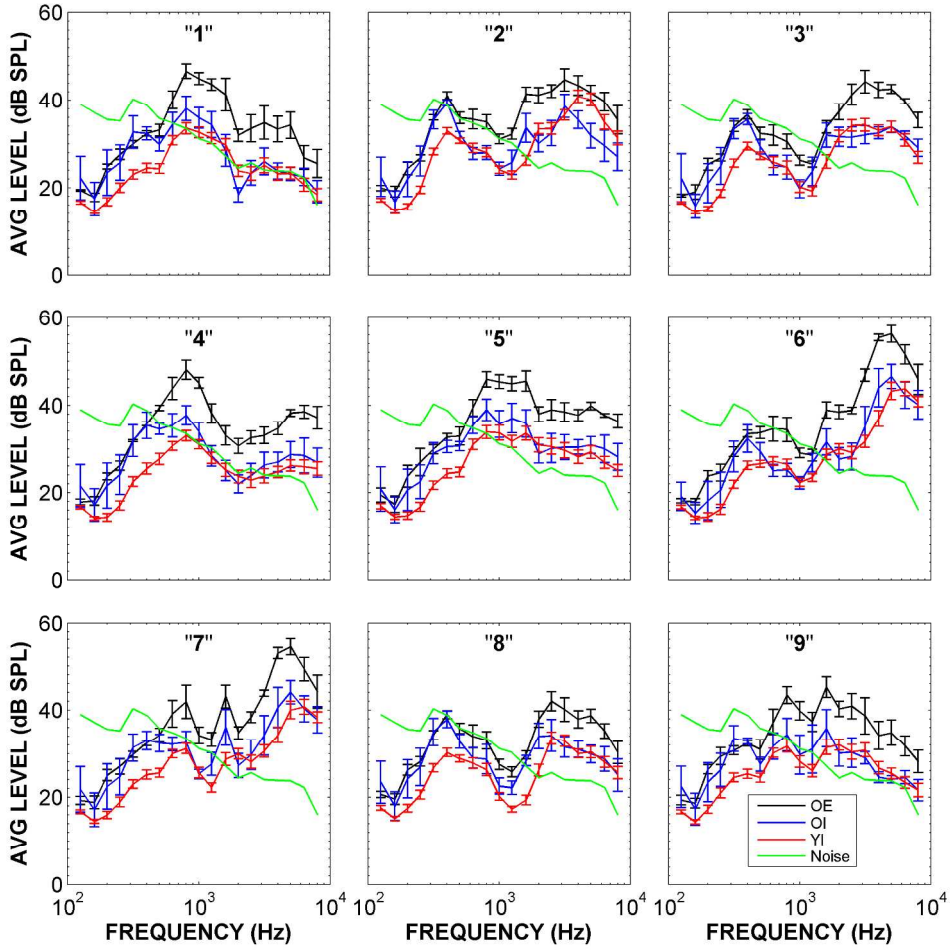

Figure 1. Average level (dB SPL) for each digit across three sessions as a function of frequency for three whisperer groups (OE, OI & YI) showing ± 1 standard deviation. Clinic room noise superimposed to show possible masking effects.
222x211mm (300 x 300 DPI)

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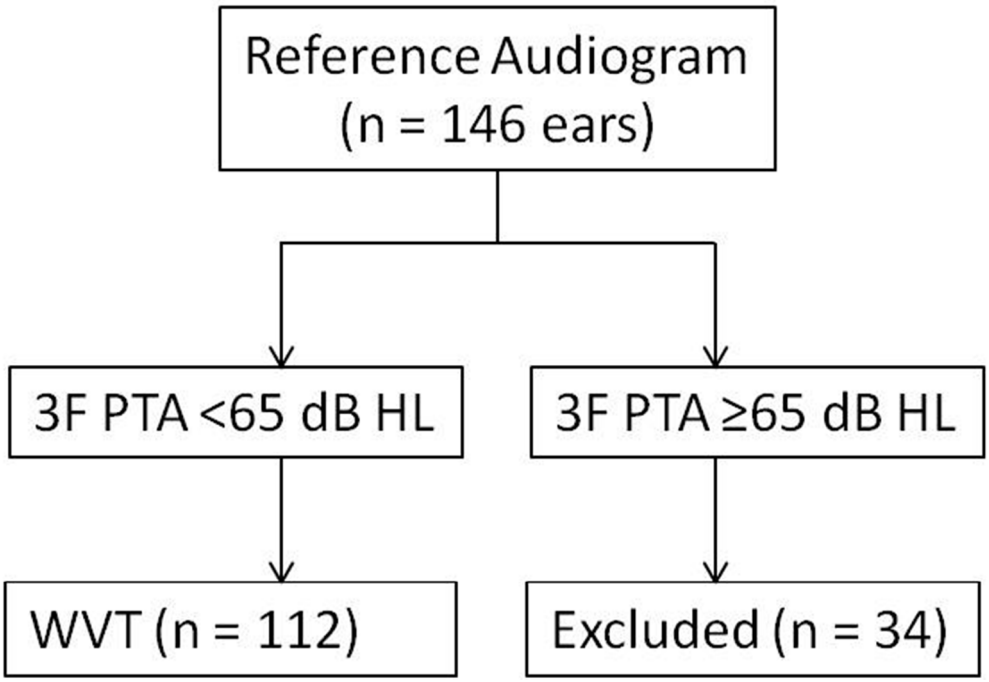

Figure 2. Flow of participants through experiment 2.
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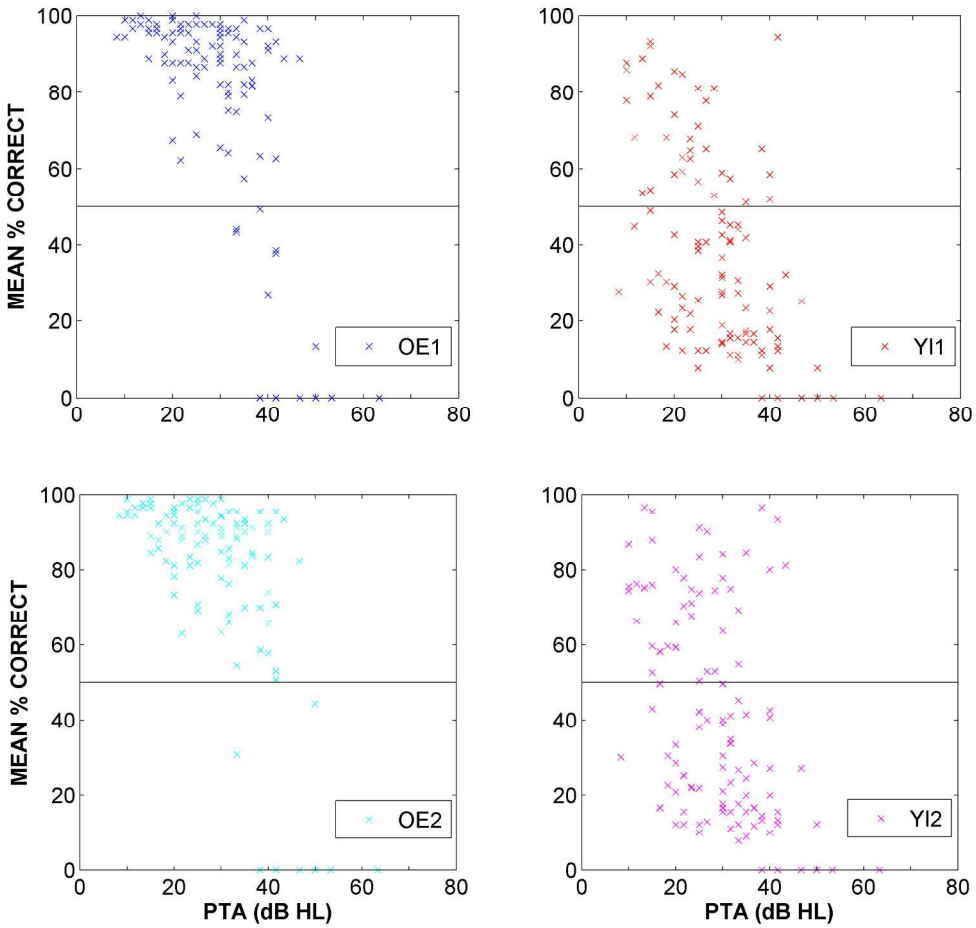

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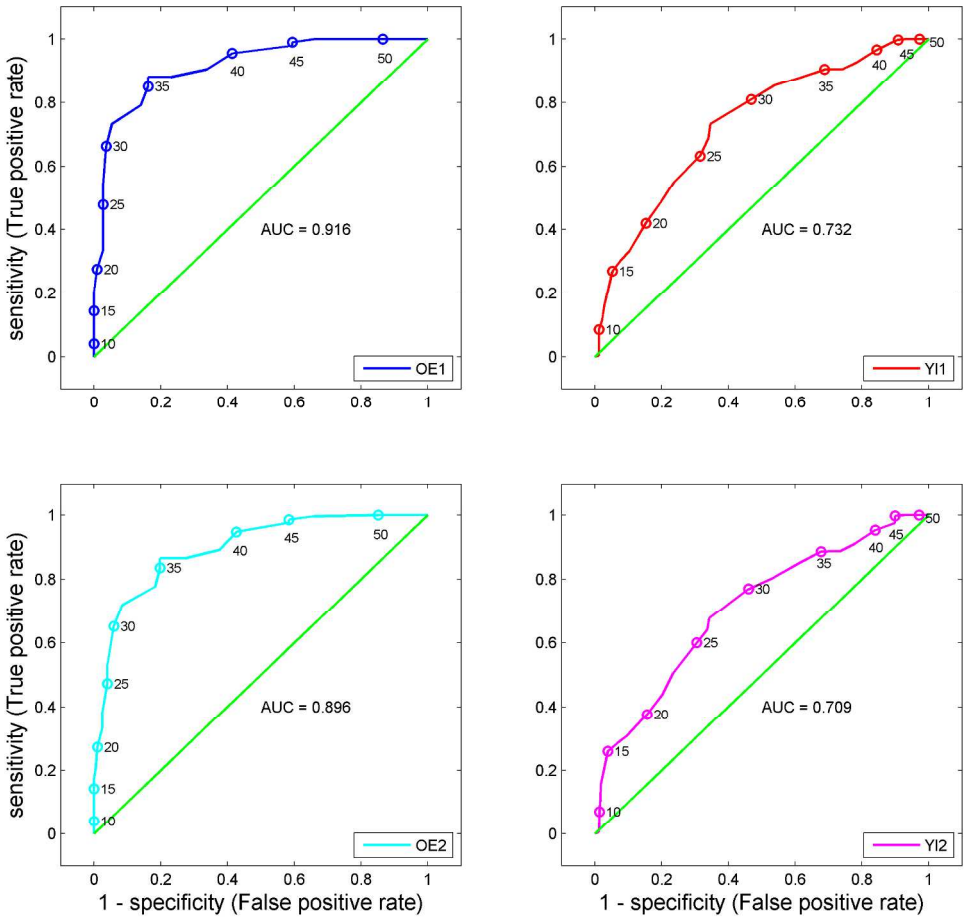

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STARD checklist for reporting of studies of diagnostic accuracy

(version January 2003)

Section and Topic	Item #		On page #	
			Exp 1	Exp 2
TITLE/ABSTRACT/ KEYWORDS	1	Identify the article as a study of diagnostic accuracy (recommend MeSH heading 'sensitivity and specificity').	1	1
INTRODUCTION	2	State the research questions or study aims, such as estimating diagnostic accuracy or comparing accuracy between tests or across participant groups.	6	6
METHODS				
Participants	3	The study population: The inclusion and exclusion criteria, setting and locations where data were collected.	7	10
	4	Participant recruitment: Was recruitment based on presenting symptoms, results from previous tests, or the fact that the participants had received the index tests or the reference standard?	7	10
	5	Participant sampling: Was the study population a consecutive series of participants defined by the selection criteria in item 3 and 4? If not, specify how participants were further selected.	7	10
	6	Data collection: Was data collection planned before the index test and reference standard were performed (prospective study) or after (retrospective study)?	NA	10
Test methods	7	The reference standard and its rationale.	9	9
	8	Technical specifications of material and methods involved including how and when measurements were taken, and/or cite references for index tests and reference standard.	8	10
	9	Definition of and rationale for the units, cut-offs and/or categories of the results of the index tests and the reference standard.	NA	11
	10	The number, training and expertise of the persons executing and reading the index tests and the reference standard.	NA	11
	11	Whether or not the readers of the index tests and reference standard were blind (masked) to the results of the other test and describe any other clinical information available to the readers.	NA	11
Statistical methods	12	Methods for calculating or comparing measures of diagnostic accuracy, and the statistical methods used to quantify uncertainty (e.g. 95% confidence intervals).	NA	14/15
	13	Methods for calculating test reproducibility, if done.	NA	NA
RESULTS				
Participants	14	When study was performed, including beginning and end dates of recruitment.	7	14
	15	Clinical and demographic characteristics of the study population (at least information on age, gender, spectrum of presenting symptoms).	7	14
	16	The number of participants satisfying the criteria for inclusion who did or did not undergo the index tests and/or the reference standard; describe why participants failed to undergo either test (a flow diagram is strongly recommended).	7	14
Test results	17	Time-interval between the index tests and the reference standard, and any treatment administered in between.	NA	10
	18	Distribution of severity of disease (define criteria) in those with the target condition; other diagnoses in participants without the target condition.	NA	14
	19	A cross tabulation of the results of the index tests (including indeterminate and missing results) by the results of the reference standard; for continuous results, the distribution of the test results by the results of the reference standard.	NA	14
	20	Any adverse events from performing the index tests or the reference standard.	NA	NA
Estimates	21	Estimates of diagnostic accuracy and measures of statistical uncertainty (e.g. 95% confidence intervals).	NA	15/16
	22	How indeterminate results, missing data and outliers of the index tests were handled.	NA	NA
	23	Estimates of variability of diagnostic accuracy between subgroups of participants, readers or centers, if done.	NA	NA
	24	Estimates of test reproducibility, if done.	NA	NA
DISCUSSION	25	Discuss the clinical applicability of the study findings.	NA	19

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The effect of experience on the sensitivity and specificity of the whispered voice test: A diagnostic accuracy study

Journal:	*BMJ Open*
Manuscript ID:	bmjopen-2012-002394.R1
Article Type:	Research
Date Submitted by the Author:	08-Mar-2013
Complete List of Authors:	McShefferty, David; MRC Institute of Hearing Research (Scottish section), Whitmer, William; MRC Institute of Hearing Research (Scottish section), Swan, Iain; University of Glasgow Akeroyd, Michael; MRC Institute of Hearing Research (Scottish section),
Primary Subject Heading:	Diagnostics
Secondary Subject Heading:	Medical education and training, Ear, nose and throat/otolaryngology
Keywords:	Sensitivity, Specificity, Hearing Tests

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Title page:

The effect of experience on the sensitivity and specificity of the whispered voice test: A diagnostic accuracy study

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Keywords: Sensitivity; specificity; Hearing Tests

Word count = 4187

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ABSTRACT

Objectives: To determine the sensitivity and specificity of the whispered voice test (WVT) in detecting hearing loss when administered by practitioners with different levels of experience.

Design: Diagnostic accuracy study of the WVT, through acoustic analysis of whispers of experienced and inexperienced practitioners (experiment 1) and behavioural validation of these recordings (experiment 2).

Setting: Research institute with a pool of patients sourced from local clinics in the Greater Glasgow area.

Participants: 22 people had their whispers recorded and analysed in experiment 1; 4 older experienced (OE), 4 older inexperienced (OI), and 14 younger inexperienced (YI). In experiment 2, 73 people (112 individual ears) took part in a digit recognition task using 2 OE and 2 YI whisperers from experiment 1.

Main outcome measures: Average level (dB SPL) across frequency, average level across all utterances (dB A), and within/across-digit deviation (dB A) for experiment 1. Sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) of the WVT for experiment 2.

Results: In experiment 1, OE whisperers were 8-10 dB more intense than inexperienced whisperers across all whispered utterances. Variability was low and comparable regardless of age or experience. In experiment 2, at an optimum threshold of 40 dB HL sensitivity and specificity were 63% (95% CI of 58% to 68%) and 93% (92% to 94%), respectively, for OE whisperers. PPV was 56% (51% to 61%), NPV was 95% (94% to 96%). For YI whisperers at an optimum threshold of 29 dB HL, sensitivity and specificity were 80% (78% to 82%) and 52% (50% to 55%). PPV was 65% (63% to 67%), NPV was 70% (67% to 72%).

Conclusions:

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The WVT is an effective screening test, providing the level of the whisperer is considered when setting the test's hearing-loss criterion. Possible implications are voice measurement while training for inexperienced whisperers.

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ARTICLE SUMMARY

Article focus

- Practitioners experienced in administering the whispered voice test have previously shown high sensitivity and specificity.
- There is a lack of research in the literature on the diagnostic accuracy of the test when it is administered by inexperienced practitioners.
- This study investigates the effect of experience on the diagnostic accuracy of the whispered voice test. How well do the recorded whispers of experienced and inexperienced practitioners screen for hearing loss?

Key messages

- For a given whisperer, variability in level across sessions and digits remains comparatively low and was not dependant on experience.
- Across all recorded digits, experienced whisperers were 8-10 dB greater in level than inexperienced whisperers.
- The level of the whisperer affects the test's performance, particularly if the whisperer is inexperienced.

Strengths and limitations

- The study provides both an acoustic analysis and behavioural validation of the whispered voice test.
- We used a closed set of responses, the digits 1-9, omitting letters and words sometimes used in the test.

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The effect of experience on the sensitivity and specificity of the whispered voice test: A diagnostic accuracy study

INTRODUCTION

The Whispered Voice Test (WVT) is an efficient screening test for detecting hearing loss. A tester stands behind and to the side of the patient, at arm's length from the patient's non-test ear, and whispers sets of either three digits or a combination of digits and letters. If the patient cannot repeat back over 50% of the test items over a minimum of two sets they are assumed to have an impairment worthy of full audiometric assessment.[1] The WVT has high sensitivity and specificity for adults if administered by an experienced practitioner,[2-5] though with less success in children.[6] The test has been used in large scale trials of approximately 15000 people[7] and is continually recommended clinically as a simple test of hearing ability.[8] It is the only test of hearing that requires no equipment at all. It would therefore be particularly valuable in situations where resources are limited.

A potential problem with the WVT is the whispers are spoken live, not pre-recorded. Random intensity differences may therefore occur which could affect the test results.[9] In addition, there are some other common disadvantages to free-field voice tests[10]: the failure to standardize the technique used, the inability to control the pitch of a whisper, the lack of control of background noise and the different acoustic properties of test environments. A review examining the accuracy of the WVT indicated that the problems of variations in technique and intensity are particularly relevant.[11] Only one study has quantified the variability in acoustic intensity of a set of English spoken digits, letters and words in a variant of the WVT used by the US Federal Highway Administration.[12] It found that this variant was not being administered as specified and showed high variability in the sound pressure level (SPL) of whispers, both between stimuli and between whisperers.

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Currently, no data exist on the level of training or experience necessary to achieve high sensitivity and specificity values from the WVT. The only data available where the WVT was validated by pure tone audiometry is that conducted by specialised professionals e.g. otolaryngologists, geriatricians or audiologists with previous experience of the test. There is one large-scale study which used trained practice nurses to administer the test, but it did not include an audiometric assessment to validate the results, nor was the amount or nature of the training specified.[7] If experience *does* affect the sensitivity and specificity of the WVT then a substantial proportion of patients may be incorrectly diagnosed. This is important both ways: a patient classed as normal-hearing when in fact they are impaired will not be referred for audiometric assessment, which may lead to social isolation, reduced quality of life and other associated health problems,[13] whereas a patient incorrectly classed as hearing-impaired would lead to a costly and unnecessary referral to an audiology department.

The present study evaluated the diagnostic accuracy of the WVT when administered by experienced and inexperienced practitioners, using both acoustic analyses and behavioural validation. The importance is that if experience does *not* affect the sensitivity and specificity, then the WVT could become a more viable screening tool, especially in resource- or equipment-limited situations where a simple, fast test of hearing is needed.

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METHODS

Experiment 1 – Acoustic analysis of whispered digits

The whispers of three groups of individuals were recorded and subject to acoustic analysis. The purpose was to quantify the variation in level of the whispers, across digits, person, and day.

Design and setting

The acoustic analysis employed three study groups: (1) an older experienced (OE) group, to establish the variability of professionals experienced in performing the WVT, (2) an intermediary group of older inexperienced (OI) whisperers, to determine if age was a factor in any acoustic differences, and (3) a larger, younger inexperienced (YI) group, to assess the variability of inexperienced whispers (we were unable to locate people for a potential fourth group, younger but experienced practitioners). The experiments were conducted at the Scottish Section of the MRC Institute of Hearing Research (IHR), located within Glasgow Royal Infirmary (GRI), UK. All data was anonymized with an index number and stored at IHR. Only the authors had access to the data.

Study population

Participants from all three groups were recruited between August 2011 and February 2012. On their initial visit each participant filled in a questionnaire relating to their first language, ethnicity and experience of the WVT. The OE group consisted of four otolaryngologists (all male, age range 50-70 years) recruited from the GRI ENT department (1 retired). Two were the authors of the original WVT paper. All were native speakers of British English. The OI group consisted of four older males (age range 41-51 years; 1 US English speaker and 3 British English speakers), with no experience of the WVT, who were recruited later from the IHR to determine if age was a factor in the intensity of whispers. The YI group was comprised of 14 inexperienced young adults (7 male, 7 female, and age range

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22-31 years) recruited from the University of Glasgow School of Medicine and IHR: 11 British English speakers, 1 Singaporean with English as a first language, 1 Italian and 1 Belgian with Italian and French as their first language respectively.

The inclusion criteria for the OE group were that they had used the WVT professionally and had at least 20 years experience in administering the test. The inclusion criteria for both OI and YI groups were that they had *not* received training and had *not* used the test professionally or in their medical or scientific studies. An additional inclusion criterion for the OI group only was that their mean age was between that of the OE and YI groups. The exclusion criteria for all groups were if they currently smoked or if they had suffered voice strain in the last two weeks; neither of these criteria led to any exclusions.

Test methods

An acoustic mannequin (Bruel & Kjaer Head and Torso Simulator, type 4100-D) was mounted on a tripod placed inside a sound-proofed audiometric booth and connected to an amplifier (Bruel & Kjaer Sound Quality Conditioning Amplifier, type 2672). The output of the amplifier was routed to a DAT recorder (Marantz PMD690/W1B) operating at a 16-bit, 48 kHz sampling rate. To ensure levels were consistent across multiple sessions, at the start of each session the ears of the mannequin were temporarily removed and a Bruel & Kjaer Calibrator (type 4230) placed over the microphones to record 1 kHz calibration tones at 94 dB SPL.

The stimuli were the digits 1-9. We omitted the letters of the alphabet, even though sometimes included in the WVT, in order to reduce recording and editing times. For each participant in each session a list was produced containing six rows of the digits 1-9. The first row was labelled ‘conversational level’: participants were asked to say the nine digits using their normal conversational voice as a warm up. The remaining five rows were labelled ‘exhaled whisper level’: participants were instructed to exhale fully before uttering each of

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these digits. The position of the digits in each row was randomized using Fisher's complete sets of orthogonal Latin squares and arranged in triplets.[14] The lists were displayed directly ahead of the participants, who were instructed to position themselves relative to the mannequin by placing their left hand on the mannequin's left tragus. With their left arm outstretched to maintain the appropriate distance of approximately 0.6 m they stood behind and slightly to the right of the mannequin's right ear (the recorded ear). Three sessions were recorded over three different days for each participant, giving 15 utterances of each whispered digit. The duration between each participant's recordings ranged from one day up to three weeks.

All recordings were edited in Adobe Audition 2.0 (Adobe Systems Inc.). A preset high-pass filter with a cut-off of 100 Hz was applied to reduce any mains or equipment hum before each digit was isolated and saved. All further processing was performed in Matlab (version 7.0.4, The Mathworks Inc.). Levels were computed in ⅓ octave bands from 100 to 8000 Hz, weighted by the standard "A"-weighting filter. All recordings and editing were conducted by one of the authors.

The outcome measures for experiment 1 were average level across frequency bands (dB SPL), average level across all whispered utterances (dB A), within digit deviation (dB A) and across digit deviation (dB A). For all outcome measures the mean value of the OE group was used as the reference standard, the rationale being that two of the four OE whisperers had shown high sensitivity and specificity values (at least 86% and 90% respectively) in previously published studies examining the WVT as a screening instrument. [1-2]

Experiment 2 – Digit recognition task

The recordings of two OE whisperers and the least-variable YI male and female whisperers were presented to the participants in a digit recognition task analogous to the

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WVT. The purpose was to quantify experimentally the effect of the differences in the two groups of whisperers, using typical pure tone audiometry as the reference test.

Study population

Participants were recruited from the available pool of patients at IHR. At the time of their invitation, no details of their hearing ability were known. The reference test was a pure-tone audiometric assessment conducted immediately before the digit recognition task.[15] All participants were treated as two single, individual ears. Inclusion followed successful completion of the audiogram, with a three-frequency (0.5, 1 & 2 kHz) pure-tone average threshold of less than 65 dB HL in the ear to be tested. A short pilot experiment had shown that participants with a threshold greater than this generally could not perform the task so any ear with this level of impairment was excluded from the digit recognition task (n = 34 ears) to avoid undue stress.

Sample size

Based on results from previous studies using a similar population, where the prevalence of hearing impairment >30 dB HL was 43%, we anticipated that clinicians would expect at least 86% sensitivity and 90% specificity.[1-2] We calculated that to obtain an estimate of sensitivity and specificity within ±10% of the anticipated values (i.e., to have 95% confidence intervals equal or less than 10% around those values), we required 108 individual ears.[16] In total 112 ears were tested.

Test methods

After a reference audiogram, participants were seated in the audiometric booth wearing headphones (AKG 720). The time interval between audiometric testing and the experimental run was at most a few minutes, being the time taken to explain the task. The stimuli were presented via PC, sound card and amplifier (Arcam A80) to the headphones. If applicable, the order of testing left and right ears was randomized. For the four whisperers chosen, all five

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runs from each of the three sessions were used giving 60 trials per ear. The order of trials was randomized for each participant, and all digits presented in a trial were from the same whisperer, session and run.

First, a practice trial was given using the conversational-level recordings of one otolaryngologist, to ensure participants could hear the digits while practising the task. Each trial consisted of at least two sequences of three digits, presented at a duty cycle of 0.8 seconds per digit. The digits were randomly chosen each time. After the first sequence a keypad was presented to the listener on a touch screen. Participants responded by entering the digits they heard and were presented with the second sequence. If after their second response they had scored <50% the trial was a fail. If they scored >50% the trial was a pass. If they had scored 50% they were presented with the final three digits from the set of nine. The total score was then calculated across all nine digits, again with a >50% correct requirement for a pass.

The stimuli were the recordings of the whispers made in experiment 1 from either two members of the OE group (as two previous studies using their whispered voices showed high sensitivity and specificity values) or the *least-variable* YI male and female whisperers. Onset and offset gates (5 ms) were applied to each digit to reduce any editing artefacts. To overcome the unrealistic nature of listening in a sound-proofed booth, a 2.6 s portion of a recording of the background noise of a typical ENT clinic room was randomly selected and presented simultaneously.

One audiologist or one of two research assistants administered the reference audiogram and the digit recognition task. All were trained and experienced in doing so. They were not blinded to the results of either test but had no control over the level of the whispers delivered by headphones - as it was controlled by a pre-written computer program - so they could not influence the digit recognition task. Two of the authors analysed the results. The

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sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) of the WVT at various levels of hearing loss were calculated for both the OE and YI stimuli. The continuity-corrected Wilson score method was used to calculate 95% confidence intervals. [17-18]

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RESULTS

Experiment 1

Figure 1 shows the results of the ⅓-octave analysis of the whispers. Each individual digit has a distinct spectrum, as would be expected from many studies of speech. Across all whispered digits the mean level of the OE group (black line) was approximately 8-10 dB greater than the means of both other groups (blue, red lines) -- see also Table 1. These mean differences between the experienced and inexperienced groups were statistically significant [$F(2, 171) = 75.4$, $p < 0.001$]. While individual differences in level were substantial, the within-whisperer variability across groups was similar. This indicated that experience affected the overall whisper level, but neither experience nor age affected the variability of whisper levels. Within-digit variability was low for all groups, at 2-3 dB. Across-digit variability was higher for all groups, at 5-6 dB, though the mean values for OE and YI groups were comparable. Note that some degree of acoustic masking could be expected from the clinic room noise (green line), particularly at frequencies below 500 Hz.

Insert Figure 1 about here

Group	OE	OI	YI
Mean *L* (dB A) across all digits	**54** (50 to 58)*	**46** (39 to 53)	**44** (42 to 47)
Mean σ (dB A) within digits	**2.0** (1.8 to 2.2)	**2.7** (2.3 to 3.0)	**2.8** (2.6 to 2.9)
Mean σ (dB A) across digits	**5.4** (4.1 to 6.8)	**6.2** (4.8 to 7.7)	**5.5** (5.0 to 6.0)

Table 1. Summary statistics for all groups showing 95% confidence intervals (*). Mean level (L, dB A) across all digits. Mean deviation (σ, dB A) within digits i.e. the mean of the mean deviation of each individual digit in the range 1-9. Mean deviation (σ, dB A) across digits i.e. the mean deviation across the full range of 1-9. All mean values reported are averaged across all whisperers in each group for all 3 sessions.

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Experiment 2

Seventy-three participants were recruited between April 2012 and June 2012: 42 males (mean age 63.2 years, range 32 to 73 years) and 31 females (mean age 62.1 years, range 35 to 73 years). From the total of 146 ears, 112 individual ears were tested and 34 ears were excluded from testing after an audiogram due to the level of impairment being ≥ 65 dB HL The three-frequency (0.5, 1 & 2 kHz) PTA values of the ears tested ranged from 8 to 63 dB HL. The mean 3F PTA across all ears tested in experiment 2 was 29 dB HL (SD 10.5 dB HL). Assuming a hearing-impairment criterion of 30 dB HL, 59 of the 112 ears (53%) exceeded this criterion.

Figure 2 shows the results of the digit-recognition task using OE and YI whisperers. Each data point represents the mean percent correct over 15 trials using one whisperer as a function of each participant's 3F PTA. Data points above the 50% threshold indicate a pass. It can be seen that the spread of the data depends upon the experience of the whisperer: both OE whisperers exhibit a clear cut-off of passes vs. fails around 40 dB HL while both YI whisperers show a lower, less clear cut-off around 30 dB HL. For YI whisperers, a substantial number of participants failed to achieve over 50% correct even when their 3F PTA was below 30 dB HL. As would be expected, performance of the participants reduced with increasing 3F PTA.

Insert Figure 2 about here

From these behavioural results, a receiver operating characteristic (ROC) analysis was performed (IBM SPSS v.19) to provide a summary statistic of the accuracy of the WVT (see Figure 3). The area under the curve (AUC) represents the ability of the test to correctly classify those who have passed and failed the test. OE1 AUC was 0.916 (95% confidence interval 0.897 to 0.935), OE2 AUC was 0.896 (0.873 to 0.918). YI1 AUC was 0.732 (0.706 to 0.757), YI2 AUC was 0.709 (0.683 to 0.734) For both OE and YI whisperers the test

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outcome was greater than chance but the OE whisperers would be expected to correctly classify approximately 20% more cases than the YI whisperers.

Insert Figure 3 about here

In order to identify the optimum threshold for discrimination of hearing loss we computed the d-prime (*d'*), the distance from the diagonal in an ROC curve over a range of criteria values for hearing impairment (10-50 dB HL in 1 dB increments). To avoid cases in which sensitivity and specificity were high, producing large *d'* values, but the positive predictive and negative predictive values (PPV and NPV, respectively) were low, we chose to limit optimal thresholds to those where all four diagnostic measures were greater than 50%. Using this criterion, the optimum pass/fail criterion occurred at 3F PTA of 40 dB HL for the OE group and at 29 dB HL for the YI group (Table 2). We also computed the Matthews correlation coefficient (MCC),[19] another single indicator of reliability, for the same range of sensitivity and specificity values as a further corroboration. The maximum MCC, indicating optimum discrimination, occurred at a 3F PTA of 38 dB HL for the OE group and 29 dB HL for the YI group. The MCC results were nearly identical to the optimal threshold determined by *d'*; since the sensitivity for the OE results at 38 dB HL was less than 50%, we chose 40 dB HL as the optimum threshold for that dataset. The sensitivity, specificity, PPV, NPV, accuracy and MCC for OE and YI whisperers with thresholds of 29 and 40 dB HL are shown in table 2. The OE results at 40 dB HL showed much higher accuracy than the YI results at 29 dB HL (23%), comparable to the respective difference in AUC found in the ROC analysis (Figure 3). The OE whisperers also showed dramatically higher specificity than YI whisperers, though lower sensitivity.

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(3F PTA) dB HL	Group	Sens	Spec	PPV	NPV	Accuracy	MCC
29	OE	23 (21 to 25)	98 (97 to 99)	93 (90 to 95)	53 (52 to 55)	59	0.31
	YI	**80 (78 to 82)**	**52 (50 to 55)**	**65 (63 to 67)**	**70 (67 to 72)**	**67**	**0.33**
40	**OE**	**63 (58 to 68)**	**93 (92 to 94)**	**56 (51 to 61)**	**95 (94 to 96)**	**90**	**0.54**
	YI	87 (83 to 90)	38 (37 to 40)	16 (14 to 17)	96 (94 to 97)	44	0.17

Table 2. Sensitivity, specificity, positive and negative predictive values (PPV and NPV, respectively) and accuracy (all as percentages) as well as Matthew's correlation coefficient (MCC) for OE and YI whisperers at two levels of hearing loss, 29 and 40 dB HL (3F PTA). The 95% confidence intervals shown in parentheses for sensitivity, specificity, PPV and NPV were obtained using the continuity-corrected Wilson score method.

While we used the 3F PTA values to classify hearing impairment in participants to comply with previous studies,[1-3] hearing impairment is also classified using a four-frequency average (4F PTA) of 0.5, 1, 2 and 4 kHz. We therefore repeated the analysis using 4F PTA values for comparison to 3F PTA results. Optimal thresholds increased slightly to 30 and 43 dB HL for YI and OE whisperers, respectively (Table 3). For OE whisperers the accuracy of the test was unchanged at the 43 dB HL threshold (90%), while at the 30 dB threshold the accuracy of the test was reduced from 59% to 47%. For YI whisperers at the 43 dB threshold the accuracy of the test increased from 44% to 54% and at the 30 dB threshold accuracy increased from 67% to 75%. At their respective optimal thresholds, both OE and YI whisperers had large increases in PPV and small reductions in NPV. Specificity increased from 52% to 65% for YI whisperers while sensitivity was unchanged. A small increase in specificity (93% to 98%) and a small reduction in sensitivity (63% to 56%) occurred for OE whisperers. Small increases in MCC value occurred for both groups at their optimal thresholds.

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(4F PTA) dB HL	Group	Sens	Spec	PPV	NPV	Accuracy	MCC
30	OE	19 (18 to 21)	100 (99 to 100)	99 (97 to 100)	40 (38 to 42)	47	0.27
	YI	**80 (78 to 81)**	**65 (62 to 68)**	**81 (79 to 83)**	**63 (60 to 66)**	**75**	**0.44**
43	**OE**	**56 (52 to 60)**	**98 (97 to 99)**	**88 (84 to 90)**	**90 (89 to 91)**	**90**	**0.65**
	YI	97 (95 to 98)	44 (42 to 46)	30 (28 to 32)	98 (97 to 99)	54	0.34

Table 3. Sensitivity, specificity, positive and negative predictive values (PPV and NPV, respectively) and accuracy (all as percentages) as well as Matthew's correlation coefficient (MCC) for OE and YI whisperers at two levels of hearing loss, 30 and 43 dB HL (4F PTA). The 95% confidence intervals shown in parentheses for sensitivity, specificity, PPV and NPV were obtained using the continuity-corrected Wilson score method.

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DISCUSSION

Statement of principal findings

The acoustic data demonstrate that the whispers from experienced practitioners of the WVT were on average 8-10 dB greater in level than whispers from those without experience. The variability in level, both within and across digits, and across sessions, was not dependent on experience. But the overall level differences across groups are a concern to those performing the WVT, as they lead to differences in the performance of the test. Variability in whispered digit level was roughly equivalent across groups (see Table 1), and deviations are similar to previously reported audiometric testing variability.[20] Inter-observer reliability was found to be low in a previous study, but the amount of experience or age of the whisperers was unspecified. [9] The sensitivity and specificity values for the test were highest at different levels of impairment for different groups of whisperers: 29 dB HL for YI whisperers and 40 dB HL for OE whisperers. The ROC analysis AUC value suggests the WVT is an 'excellent' test for experienced whisperers but only an 'acceptable' test for inexperienced whisperers.[21] This is perhaps overstating the overall discriminatory power of the test. Accuracy levels were as low as 47% at a 4F PTA of 30 dB HL using OE whisperers but reached 90% accuracy at 40 dB HL (3F PTA) and 43 dB HL (4F PTA).

Strengths and weaknesses of the study

A strength of this study is that it provides both an acoustic analysis and behavioural validation of the WVT. The acoustic analysis showed clear level differences based on experience with the test, but no clear differences in level variance. The behavioural validation showed clear differences in the optimal threshold of the WVT based on the tester's experience. Another strength of this study was that both the older experienced whisperers used in experiment 2 were the authors of two previous studies of the WVT.[1-2] There they reported that the majority of those with ≤30 dB HL could hear a whispered voice at a distance

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of 60 cm while the majority of those with ≥30 dB HL threshold could not. This provided a base-line of the diagnostic accuracy that OE whisperers could achieve. It is possible that using two authors from previous studies on the WVT as whisperers is not a representative sample of the OE population and is potentially a weakness of our study. However, both had at least 20 years experience in administering the test and the results from their studies were comparable to others in which other authors also administered the test. [3, 6] No other studies have been found which identify what a representative sample of the OE population would be.

A potential weakness is that the increased threshold of 40 dB HL for the experienced whisperers in this study may be due to differences between our laboratory validation and clinical practice (e.g. pre-recorded stimuli delivered via headphones, and a closed set of responses). Based on our results, the test appears to be less reliable in those patients with lower levels of impairment who would benefit most from screening for hearing loss. Unlike the clinical testing where a patient is not given any indication of what is being whispered, participants in this study were given a closed set of responses (i.e. the digits 1-9), potentially inflating their results.

Another weakness of the current study is that other potential tokens were not tested, such as letters or words. This decision was made due to experimental time constraints. Nevertheless, we doubt that the acoustics of the whispering of single letters or words would be so different to the whispering of single digits that the results would be affected substantially. Despite these potential weaknesses, our results do show that experience does affect the sensitivity, specificity and overall accuracy of the WVT.

Meaning of the study: Possible mechanisms and implications for policy makers

This study raises the question of training in the use of the WVT. The study by Smeeth et al. used trained practice nurses,[7] but the amount of training and experience was

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unspecified. It is also not clear whether the majority of those who regularly administer the test have ever measured their whispered voice level, and if so, in what setting. It is obviously impractical to measure voice level before administering the test in common practice, however we believe training in the WVT should include voice level measurement. We therefore do not recommend that the WVT be administered by an inexperienced practitioner who does not know the acoustic level of their whispers.

An experienced and properly trained practitioner could provide substantial cost benefits when screening for hearing loss. The WVT can be administered in less than one minute in any quiet setting in comparison to an expensive and time consuming referral to an audiology department. The low variability in level is commensurate with (more expensive) pre-recorded calibration.

Unanswered questions and future research

We classified whisperers into two groups, experienced and inexperienced. It would be useful to extend this to a continuous dimension of experience rather than a binary classification.

All of the participants in experiment 2 of this study, both whisperers and listeners, were British with English as a first language. Given the spectro-temporal variation in digits across languages, similar results could be expected for other languages common to both whisperer and listener. When applied in a listeners non-native language, performance in speech recognition is often worse,[22] but it is unclear how whispered speech performance would be affected. Despite its drawbacks, the WVT remains the only test of hearing that needs no equipment and can therefore be used in many circumstances where other hearing tests would be unwelcome. Further investigation and refinement of the test would be valuable. It would be of particular interest to know (1) if people can be trained to reliably produce whispers at a

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given – not their innate – level, (2) how the level of whispers depends on whether they are made before or after exhaling, and (3) how using more than one *trained* whisperer in the test affects the sensitivity and specificity.

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Acknowledgements: We thank all participants from both experiments; Patrick Howell, Neil Kirk and Kay Foreman for collecting the data; Oliver Zobay for his statistical advice; Professor George Browning for his advice and assistance with this study; and the reviewers for their comments on a previous version of this manuscript.

Contributors: WW and DM participated in the study design, supervised recruitment of participants and analysed the data. All authors drafted the manuscript and/or contributed to its revision, and approved the final version. DM is guarantor.

Funding: The Scottish section of the IHR is supported by intramural funding from the Medical Research Council (grant number U135097131) and the Chief Scientist Office of the Scottish Government.

Competing interests: All authors have completed the Unified Competing interest form at www.icmje.org/coi_disclosure.pdf (available on request from the corresponding author) and declare: no financial relationships with any organisations that might have an interest in the submitted work in the previous three years; no other relationships or activities that could appear to have influenced the submitted work.

Ethical approval: This study was approved by the West of Scotland research ethics service (WoS REC(4) 09/S0704/12). All participants gave informed consent.

Data sharing: No additional data available.

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Figure Legends:

Figure 1. Average level (dB SPL) for each digit across three sessions as a function of frequency for three whisperer groups (OE, OI & YI) showing ± 1 standard deviation. Clinic room noise superimposed to show possible masking effects.

Figure 2. Mean percent correct over 15 simulated whispered voice test trials as a function of three-frequency pure-tone average (PTA) hearing loss for 112 individual ears tested with the recordings of 2 OE and 2 YI whisperers. Data points above the 50% threshold indicate a pass.

Figure 3. ROC analysis for experienced and inexperienced whisperers, showing sensitivity as a function of false positive rate for each whisperer (separate panels). Points along the curve are labelled in 5 dB HL increments, and the total area under the curve (AUC) is given below the diagonal.

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Title page:

The effect of experience on the sensitivity and specificity of the whispered voice test: A diagnostic accuracy study

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Keywords: Sensitivity; specificity; Hearing Tests

Word count = ~~37944~~4187

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ABSTRACT

Objectives: To determine the sensitivity and specificity of the whispered voice test (WVT) in detecting hearing loss when administered by practitioners with different levels of experience.

Design: Diagnostic accuracy study of the WVT, through acoustic analysis of whispers of experienced and inexperienced practitioners (experiment 1) and behavioural validation of these recordings (experiment 2).

Setting: Research institute with a pool of patients sourced from local clinics in the Greater Glasgow area.

Participants: 22 people had their whispers recorded and analysed in experiment 1; 4 older experienced (OE), 4 older inexperienced (OI), and 14 younger inexperienced (YI). In experiment 2, 73 people (112 individual ears) took part in a digit recognition task using 2 OE and 2 YI whisperers from experiment 1.

Main outcome measures: Average level (dB SPL) across frequency, average level across all utterances (dB A), and within/across-digit deviation (dB A) for experiment 1. Sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) of the WVT for experiment 2.

Results: In experiment 1, OE whisperers were 8-10 dB more intense than inexperienced whisperers across all whispered utterances. Variability was low and comparable regardless of age or experience. In experiment 2, at an optimum threshold of 40 dB HL sensitivity and specificity were 63% (95% CI of 58% to 68%) and 93% (92% to 94%), respectively, for OE whisperers. PPV was 56% (51% to 61%), NPV was 95% (94% to 96%). For YI whisperers at an optimum threshold of 29 dB HL, sensitivity and specificity were 80% (78% to 82%) and 52% (50% to 55%). PPV was 65% (63% to 67%), NPV was 70% (67% to 72%).

Conclusions:

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The WVT is an effective screening test, providing the level of the whisperer is considered when setting the test's hearing-loss criterion. Possible implications are voice measurement while training for inexperienced whisperers.

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ARTICLE SUMMARY

Article focus

- Practitioners experienced in administering the whispered voice test have previously shown high sensitivity and specificity.
- There is a lack of research in the literature on the diagnostic accuracy of the test when it is administered by inexperienced practitioners.
- This study investigates the effect of experience on the diagnostic accuracy of the whispered voice test. How well do the recorded whispers of experienced and inexperienced practitioners screen for hearing loss?

Key messages

- For a given whisperer, variability in level across sessions and digits remains comparatively low and was not dependant on experience.
- Across all recorded digits, experienced whisperers were 8-10 dB greater in level than inexperienced whisperers.
- The level of the whisperer affects the test's performance, particularly if the whisperer is inexperienced.

Strengths and limitations

- The study provides both an acoustic analysis and behavioural validation of the whispered voice test.
- We used a closed set of responses, the digits 1-9, omitting letters and words sometimes used in the test.

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The effect of experience on the sensitivity and specificity of the whispered voice test: A diagnostic accuracy study

INTRODUCTION

The Whispered Voice Test (WVT) is an efficient screening test for detecting hearing loss. A tester stands behind and to the side of the patient, at arm's length from the patient's non-test ear, and whispers sets of either three digits or a combination of digits and letters. If the patient cannot repeat back over 50% of the test items over a minimum of two sets they are assumed to have an impairment worthy of full audiometric assessment.[1] The WVT has high sensitivity and specificity for adults if administered by an experienced practitioner,[2-5] though with less success in children.[6] The test has been used in large scale trials of approximately 15000 people[7] and is continually recommended clinically as a simple test of hearing ability.[8] It is the only test of hearing that requires no equipment at all. It would therefore be particularly valuable in situations where resources are limited.

A potential problem with the WVT is the whispers are spoken live, not pre-recorded. Random intensity differences may therefore occur which could affect the test results.[9] In addition, there are some other common disadvantages to free-field voice tests[10]: the failure to standardize the technique used, the inability to control the pitch of a whisper, the lack of control of background noise and the different acoustic properties of test environments. A review examining the accuracy of the WVT indicated that the problems of variations in technique and intensity are particularly relevant.[11] Only one study has quantified the variability in acoustic intensity of a set of English spoken digits, letters and words in a variant of the WVT used by the US Federal Highway Administration.[12] It found that this variant was not being administered as specified and showed high variability in the sound pressure level (SPL) of whispers, both between stimuli and between whisperers.

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Currently, no data exist on the level of training or experience necessary to achieve high sensitivity and specificity values from the WVT. The only data available where the WVT was validated by pure tone audiometry is that conducted by specialised professionals e.g. otolaryngologists, geriatricians or audiologists with previous experience of the test. There is one large-scale study which used trained practice nurses to administer the test, but it did not include an audiometric assessment to validate the results, nor was the amount or nature of the training specified.[7] If experience *does* affect the sensitivity and specificity of the WVT then a substantial proportion of patients may be incorrectly diagnosed. This is important both ways: a patient classed as normal-hearing when in fact they are impaired will not be referred for audiometric assessment, which may lead to social isolation, reduced quality of life and other associated health problems,[13] whereas a patient incorrectly classed as hearing-impaired would lead to a costly and unnecessary referral to an audiology department.

The present study evaluated the diagnostic accuracy of the WVT when administered by experienced and inexperienced practitioners, using both acoustic analyses and behavioural validation. The importance is that if experience does *not* affect the sensitivity and specificity, then the WVT could become a more viable screening tool, especially in resource- or equipment-limited situations where a simple, fast test of hearing is needed.

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METHODS

Experiment 1 – Acoustic analysis of whispered digits

The whispers of three groups of individuals were recorded and subject to acoustic analysis. The purpose was to quantify the variation in level of the whispers, across digits, person, and day.

Design and setting

The acoustic analysis employed three study groups: (1) an older experienced (OE) group, to establish the variability of professionals experienced in performing the WVT, (2) an intermediary group of older inexperienced (OI) whisperers, to determine if age was a factor in any acoustic differences, and (3) a larger, younger inexperienced (YI) group, to assess the variability of inexperienced whispers (we were unable to locate people for a potential fourth group, younger but experienced practitioners). The experiments were conducted at the Scottish Section of the MRC Institute of Hearing Research (IHR), located within Glasgow Royal Infirmary (GRI), UK. All data was anonymized with an index number and stored at IHR. Only the authors had access to the data.

Study population

Participants from all three groups were recruited between August 2011 and February 2012. On their initial visit each participant filled in a questionnaire relating to their first language, ethnicity and experience of the WVT. The OE group consisted of four otolaryngologists (all male, age range 50-70 years) recruited from the GRI ENT department (1 retired). Two were the authors of the original WVT paper. All were native speakers of British English. The OI group consisted of four older males (age range 41-51 years; 1 US English speaker and 3 British English speakers), with no experience of the WVT, who were recruited later from the IHR to determine if age was a factor in the intensity of whispers. The YI group was comprised of 14 inexperienced young adults (7 male, 7 female, and age range

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22-31 years) recruited from the University of Glasgow School of Medicine and IHR: 11 British English speakers, 1 Singaporean with English as a first language, 1 Italian and 1 Belgian with Italian and French as their first language respectively.

The inclusion ~~criterion~~ criteria for the OE group ~~was~~ were that they had used the WVT professionally and had at least 20 years experience in administering the test. The inclusion criteria for both OI and YI groups were that they had *not* received training and had *not* used the test professionally or in their medical or scientific studies. An additional inclusion criterion for the OI group only was that their mean age was between that of the OE and YI groups. The exclusion criteria for all groups were if they currently smoked or if they had suffered voice strain in the last two weeks; neither of these criteria led to any exclusions.

Test methods

An acoustic mannequin (Bruel & Kjaer Head and Torso Simulator, type 4100-D) was mounted on a tripod placed inside a sound-proofed audiometric booth and connected to an amplifier (Bruel & Kjaer Sound Quality Conditioning Amplifier, type 2672). The output of the amplifier was routed to a DAT recorder (Marantz PMD690/W1B) operating at a 16-bit, 48 kHz sampling rate. To ensure levels were consistent across multiple sessions, at the start of each session the ears of the mannequin were temporarily removed and a Bruel & Kjaer Calibrator (type 4230) placed over the microphones to record 1 kHz calibration tones at 94 dB SPL.

The stimuli were the digits 1-9. We omitted the letters of the alphabet, even though sometimes included in the WVT, in order to reduce recording and editing times. For each participant in each session a list was produced containing six rows of the digits 1-9. The first row was labelled 'conversational level': participants were asked to say the nine digits using their normal conversational voice as a warm up. The remaining five rows were labelled 'exhaled whisper level': participants were instructed to exhale fully before uttering each of

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these digits. The position of the digits in each row was randomized using Fisher's complete sets of orthogonal Latin squares and arranged in triplets.[14] The lists were displayed directly ahead of the participants, who were instructed to position themselves relative to the mannequin by placing their left hand on the mannequin's left tragus. With their left arm outstretched to maintain the appropriate distance of approximately 0.6 m they stood behind and slightly to the right of the mannequin's right ear (the recorded ear). Three sessions were recorded over three different days for each participant, giving 15 utterances of each whispered digit. The duration between each participant's recordings ranged from one day up to three weeks.

All recordings were edited in Adobe Audition 2.0 (Adobe Systems Inc.). A preset high-pass filter with a cut-off of 100 Hz was applied to reduce any mains or equipment hum before each digit was isolated and saved. All further processing was performed in Matlab (version 7.0.4, The Mathworks Inc.). Levels were computed in ⅓ octave bands from 100 to 8000 Hz, weighted by the standard "A"-weighting filter. All recordings and editing were conducted by one of the authors ~~(DM)~~.

The outcome measures for experiment 1 were average level across frequency bands (dB SPL), average level across all whispered utterances (dB A), within digit deviation (dB A) and across digit deviation (dB A). For all outcome measures the mean value of the OE group was used as the reference standard, the rationale being that two of the four OE whisperers had shown high sensitivity and specificity values (at least 86% and 90% respectively) in previously published studies examining the WVT as a screening instrument.[1-2]

Experiment 2 – Digit recognition task

The recordings of two OE whisperers and the least-variable YI male and female whisperers were presented to the participants in a digit recognition task analogous to the

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WVT. The purpose was to quantify experimentally the effect of the differences in the two groups of whisperers, using typical pure tone audiometry as the reference test.

Study population

Participants were recruited from the available pool of patients at IHR. At the time of their invitation, no details of their hearing ability were known. The reference test was a pure-tone audiometric assessment conducted immediately before the digit recognition task.[15] All participants were treated as two single, individual ears. Inclusion followed successful completion of the audiogram, with a three-frequency (0.5, 1 & 2 kHz) pure-tone average threshold of less than 65 dB HL in the ear to be tested. A short pilot experiment had shown that participants with a threshold greater than this generally could not perform the task so any ear with this level of impairment was excluded from the digit recognition task (n = 34 ears) to avoid undue stress.

Sample size

Based on results from previous studies using a similar population, where the prevalence of hearing impairment >30 dB HL was 43%, we anticipated that clinicians would expect at least 86% sensitivity and 90% specificity.[1-2] We calculated that to obtain an estimate of sensitivity and specificity within ±10% of the anticipated values (i.e., to have 95% confidence intervals equal or less than 10% around those values), we required 108 individual ears.[16] In total 112 ears were tested.

Test methods

After a reference audiogram, participants were seated in the audiometric booth wearing headphones (AKG 720). The time interval between audiometric testing and the experimental run was at most a few minutes, being the time taken to explain the task. The stimuli were presented via PC, sound card and amplifier (Arcam A80) to the headphones. If applicable, the order of testing left and right ears was randomized. For the four whisperers chosen, all five

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runs from each of the three sessions were used giving 60 trials per ear. The order of trials was randomized for each participant, and all digits presented in a trial were from the same whisperer, session and run.

~~First, a practice trial was given using the most intense conversational-level recordings of one otolaryngologist.~~ First, a practice trial was given using the conversational-level recordings of one otolaryngologist, to ensure participants could hear the digits while practising the task. Each trial consisted of at least two sequences of three digits, presented at a duty cycle of 0.8 seconds per digit. The digits were randomly chosen each time. After the first sequence a keypad was presented to the listener on a touch screen. Participants responded by entering the digits they heard and were presented with the second sequence. If after their second response they had scored <50% the trial was a fail. If they scored >50% the trial was a pass. If they had scored 50% they were presented with the final three digits from the set of nine. The total score was then calculated across all nine digits, again with a >50% correct requirement for a pass.

The stimuli were the recordings of the whispers made in experiment 1 from either two members of the OE group (as two previous studies using their whispered voices showed high sensitivity and specificity values) or the *least-variable* YI male and female whisperers. Onset and offset gates (5 ms) were applied to each digit to reduce any editing artefacts. To overcome the unrealistic nature of listening in a sound-proofed booth, a 2.6 s portion of a recording of the background noise of a typical ENT clinic room was randomly selected and presented simultaneously.

One audiologist or one of two research assistants administered the reference audiogram and the digit recognition task. All were trained and experienced in doing so. They were not blinded to the results of either test but had no control over the level of the whispers delivered by headphones - as it was controlled by a pre-written computer program - so they

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could not influence the digit recognition task. Two of the authors ~~(DM, WW)~~ analysed the results. The sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) of the WVT at various levels of hearing loss were calculated for both the OE and YI stimuli. The continuity-corrected Wilson score method was used to calculate 95% confidence intervals. [17-18]

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RESULTS

Experiment 1

Figure 1 shows the results of the ⅓-octave analysis of the whispers. Each individual digit has a distinct spectrum, as would be expected from many studies of speech. Across all whispered digits the mean level of the OE group (black line) was approximately 8-10 dB greater than the means of both other groups (blue, red lines) -- see also Table 1. These mean differences between the experienced and inexperienced groups were statistically significant [$F(2, 171) = 75.4$, $p < 0.001$]. While individual differences in level were substantial, the within-whisperer variability across groups was similar. This indicated that experience affected the overall whisper level, but neither experience nor age affected the variability of whisper levels. Within-digit variability was low for all groups, at 2-3 dB. Across-digit variability was higher for all groups, at 5-6 dB, though the mean values for OE and YI groups were comparable. Note that some degree of acoustic masking could be expected from the clinic room noise (green line), particularly at frequencies below 500 Hz.

Insert Figure 1 about here

Group	OE	OI	YI
Mean *L* (dB A) across all digits	**54** (50 to 58)*	**46** (39 to 53)	**44** (42 to 47)
Mean σ (dB A) within digits	**2.0** (1.8 to 2.2)	**2.7** (2.3 to 3.0)	**2.8** (2.6 to 2.9)
Mean σ (dB A) across digits	**5.4** (4.1 to 6.8)	**6.2** (4.8 to 7.7)	**5.5** (5.0 to 6.0)

Table 1. Summary statistics for all groups showing 95% confidence intervals (*). Mean level (L, dB A) across all digits. Mean deviation (σ, dB A) within digits i.e. the mean of the mean deviation of each individual digit in the range 1-9. Mean deviation (σ, dB A) across digits i.e. the mean deviation across the full range of 1-9. All mean values reported are averaged across all whisperers in each group for all 3 sessions.

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Experiment 2

Seventy-three participants were recruited between April 2012 and June 2012: 42 males (mean age 63.2 years, range 32 to 73 years) and 31 females (mean age 62.1 years, range 35 to 73 years). From the total of 146 ears, 112 individual ears were tested and 34 ears were excluded from testing after an audiogram due to the level of impairment being ≥ 65 dB HL ~~(figure 2).~~ The three-frequency (0.5, 1 & 2 kHz) PTA values of the ears tested ranged from 8 to 63 dB HL. The mean 3F PTA across all ears tested in experiment 2 was 29 dB HL (SD 10.5 dB HL). Assuming a hearing-impairment criterion of 30 dB HL, 59 of the 112 ears (53%) exceeded this criterion.

~~*Insert Figure 2 about here*~~

Figure ~~3~~ 2 shows the results of the digit-recognition task using OE and YI whisperers. Each data point represents the mean percent correct over 15 trials using one whisperer as a function of each participant's 3F PTA. Data points above the 50% threshold indicate a pass. It can be seen that the spread of the data depends upon the experience of the whisperer: both OE whisperers exhibit a clear cut-off of passes vs. fails around 40 dB HL while both YI whisperers show a lower, less clear cut-off around 30 dB HL. For YI whisperers, a substantial number of participants failed to achieve over 50% correct even when their 3F PTA was below 30 dB HL. As would be expected, performance of the participants reduced with increasing 3F PTA.

Insert Figure ~~3~~ 2 about here

From these behavioural results, a receiver operating characteristic (ROC) analysis was performed (IBM SPSS v.19) to provide a summary statistic of the accuracy of the WVT (see Figure ~~4~~3). The area under the curve (AUC) represents the ability of the test to correctly classify those who have passed and failed the test. OE1 AUC was 0.916 (95% confidence interval 0.897 to 0.935), OE2 AUC was 0.896 (0.873 to 0.918). YI1 AUC was 0.732 (0.706

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to 0.757), YI2 AUC was 0.709 (0.683 to 0.734) For both OE and YI whisperers the test outcome was greater than chance but the OE whisperers would be expected to correctly classify approximately 20% more cases than the YI whisperers.

Insert Figure ~~4~~ 3 about here

In order to identify the optimum threshold for discrimination of hearing loss we computed the d-prime (*d'*), the distance from the diagonal in an ROC curve over a range of criteria values for hearing impairment (10-50 dB HL in 1 dB increments). To avoid cases in which sensitivity and specificity were high, producing large *d'* values, but the positive predictive and negative predictive values (PPV and NPV, respectively) were low, we chose to limit optimal thresholds to those where all four diagnostic measures were greater than 50%. Using this criterion, the optimum pass/fail criterion occurred at 3F PTA of 40 dB HL for the OE group and at 29 dB HL for the YI group (Table 2). We also computed the Matthews correlation coefficient (MCC),[19] another single indicator of reliability, for the same range of sensitivity and specificity values as a further corroboration. The maximum MCC, indicating optimum discrimination, occurred at a 3F PTA of 38 dB HL for the OE group and 29 dB HL for the YI group. The MCC results were nearly identical to the optimal threshold determined by *d'*; since the sensitivity for the OE results at 38 dB HL was less than 50%, we chose 40 dB HL as the optimum threshold for that dataset. The sensitivity, specificity, PPV, NPV, accuracy and MCC for OE and YI whisperers with thresholds of 29 and 40 dB HL are shown in table 2. The OE results at 40 dB HL showed much higher accuracy than the YI results at 29 dB HL (23%), comparable to the respective difference in AUC found in the ROC analysis (Figure ~~4~~3). The OE whisperers also showed dramatically higher specificity than YI whisperers, though lower sensitivity.

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(3F PTA) dB HL	Group	Sens	Spec	PPV	NPV	Accuracy	MCC
29	OE	23 (21 to 25)	98 (97 to 99)	93 (90 to 95)	53 (52 to 55)	59	0.31
	YI	**80 (78 to 82)**	**52 (50 to 55)**	**65 (63 to 67)**	**70 (67 to 72)**	**67**	**0.33**
40	**OE**	**63 (58 to 68)**	**93 (92 to 94)**	**56 (51 to 61)**	**95 (94 to 96)**	**90**	**0.54**
	YI	87 (83 to 90)	38 (37 to 40)	16 (14 to 17)	96 (94 to 97)	44	0.17

Table 2. Sensitivity, specificity, positive and negative predictive values (PPV and NPV, respectively) and accuracy (all as percentages) as well as Matthew's correlation coefficient (MCC) for OE and YI whisperers at two levels of hearing loss, 29 and 40 dB HL (3F PTA). The 95% confidence intervals shown in parentheses for sensitivity, specificity, PPV and NPV were obtained using the continuity-corrected Wilson score method.

While we used the 3F PTA values to classify hearing impairment in participants to comply with previous studies,[1-3] hearing impairment is also classified using a four-frequency average (4F PTA) of 0.5, 1, 2 and 4 kHz. We therefore repeated the analysis using 4F PTA values for comparison to 3F PTA results. Optimal thresholds increased slightly to 30 and 43 dB HL for YI and OE whisperers, respectively (Table 3). For OE whisperers the accuracy of the test was unchanged at the 43 dB HL threshold (90%), while at the 30 dB threshold the accuracy of the test was reduced from 59% to 47%. For YI whisperers at the 43 dB threshold the accuracy of the test increased from 44% to 54% and at the 30 dB threshold accuracy increased from 67% to 75%. At their respective optimal thresholds, both OE and YI whisperers had large increases in PPV and small reductions in NPV. Specificity increased from 52% to 65% for YI whisperers while sensitivity was unchanged. A small increase in specificity (93% to 98%) and a small reduction in sensitivity (63% to 56%) occurred for OE whisperers. Small increases in MCC value occurred for both groups at their optimal thresholds.

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(4F PTA) dB HL	Group	Sens	Spec	PPV	NPV	Accuracy	MCC
30	OE	19 (18 to 21)	100 (99 to 100)	99 (97 to 100)	40 (38 to 42)	47	0.27
	YI	**80 (78 to 81)**	**65 (62 to 68)**	**81 (79 to 83)**	**63 (60 to 66)**	**75**	**0.44**
43	**OE**	**56 (52 to 60)**	**98 (97 to 99)**	**88 (84 to 90)**	**90 (89 to 91)**	**90**	**0.65**
	YI	97 (95 to 98)	44 (42 to 46)	30 (28 to 32)	98 (97 to 99)	54	0.34

Table 3. Sensitivity, specificity, positive and negative predictive values (PPV and NPV, respectively) and accuracy (all as percentages) as well as Matthew's correlation coefficient (MCC) for OE and YI whisperers at two levels of hearing loss, 30 and 43 dB HL (4F PTA). The 95% confidence intervals shown in parentheses for sensitivity, specificity, PPV and NPV were obtained using the continuity-corrected Wilson score method.

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DISCUSSION

Statement of principal findings

The acoustic data demonstrate that the whispers from experienced practitioners of the WVT were on average 8-10 dB greater in level than whispers from those without experience. The variability in level, both within and across digits, and across sessions, was not dependent on experience. But the overall level differences across groups are a concern to those performing the WVT, as they lead to differences in the performance of the test. Variability in whispered digit level was roughly equivalent across groups (see Table 1), and deviations are similar to previously reported audiometric testing variability.[20] Inter-observer reliability was found to be low in a previous study, but the amount of experience or age of the whisperers was unspecified. [9] The sensitivity and specificity values for the test were highest at different levels of impairment for different groups of whisperers: 29 dB HL for YI whisperers and 40 dB HL for OE whisperers. The ROC analysis AUC value suggests the WVT is an 'excellent' test for experienced whisperers but only an 'acceptable' test for inexperienced whisperers.[21] This is perhaps overstating the overall discriminatory power of the test. Accuracy levels were as low as 47% at a 4F PTA of 30 dB HL using OE whisperers but reached 90% accuracy at 40 dB HL (3F PTA) and 43 dB HL (4F PTA).

Strengths and weaknesses of the study

A strength of this study is that it provides both an acoustic analysis and behavioural validation of the WVT. The acoustic analysis showed clear level differences based on experience with the test, but no clear differences in level variance. The behavioural validation showed clear differences in the optimal threshold of the WVT based on the tester's experience. Another strength of this study was that both the older experienced whisperers used in experiment 2 were the authors of two previous studies of the WVT.[1-2] There they reported that the majority of those with ≤30 dB HL could hear a whispered voice at a distance

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of 60 cm while the majority of those with ≥30 dB HL threshold could not. This provided a base-line of the diagnostic accuracy that OE whisperers could achieve. It is possible that using two authors from previous studies on the WVT as whisperers is not a representative sample of the OE population and is potentially a weakness of our study. However, both had at least 20 years experience in administering the test and the results from their studies were comparable to others in which other authors also administered the test. [3, 6] No other studies have been found which identify what a representative sample of the OE population would be.

A potential weakness is that the increased threshold of 40 dB HL for the experienced whisperers in this study may be due to differences between our laboratory validation and clinical practice (e.g. pre-recorded stimuli delivered via headphones, and a closed set of responses). Based on our results, the test appears to be less reliable in those patients with lower levels of impairment who would benefit most from screening for hearing loss. Unlike the clinical testing where a patient is not given any indication of what is being whispered, participants in this study were given a closed set of responses (i.e. the digits 1-9), potentially inflating their results.

Another weakness of the current study is that other potential tokens were not tested, such as letters or words. This decision was made due to experimental time constraints. Nevertheless, we doubt that the acoustics of the whispering of single letters or words would be so different to the whispering of single digits that the results would be affected substantially. Despite these potential weaknesses, our results do show that experience does affect the sensitivity, specificity and overall accuracy of the WVT.

Meaning of the study: Possible mechanisms and implications for policy makers

This study raises the question of training in the use of the WVT. The study by Smeeth et al. used trained practice nurses,[7] but the amount of training and experience was

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unspecified. It is also not clear whether the majority of those who regularly administer the test have ever measured their whispered voice level, and if so, in what setting. It is obviously impractical to measure voice level before administering the test in common practice, however we believe training in the WVT should include voice level measurement. We therefore do not recommend that the WVT be administered by an inexperienced practitioner who does not know the acoustic level of their whispers.

An experienced and properly trained practitioner could provide substantial cost benefits when screening for hearing loss. The WVT can be administered in less than one minute in any quiet setting in comparison to an expensive and time consuming referral to an audiology department. The low variability in level is commensurate with (more expensive) pre-recorded calibration.

Unanswered questions and future research

We classified whisperers into two groups, experienced and inexperienced. It would be useful to extend this to a continuous dimension of experience rather than a binary classification.

All of the participants in experiment 2 of this study, both whisperers and listeners, were British with English as a first language. Given the spectro-temporal variation in digits across languages, similar results could be expected for other languages common to both whisperer and listener. When applied in a listeners non-native language, performance in speech recognition is often worse,[22] but it is unclear how whispered speech performance would be affected.

Despite its drawbacks, the WVT remains the only test of hearing that needs no equipment and can therefore be used in many circumstances where other hearing tests would be unwelcome. Further investigation and refinement of the test would be valuable. It would

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be of particular interest to know (1) if people can be trained to reliably produce whispers at a given – not their innate – level, (2) how the level of whispers depends on whether they are made before or after exhaling, and (3) how using more than one *trained* whisperer in the test affects the sensitivity and specificity.

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Acknowledgements: We thank all participants from both experiments; Patrick Howell, Neil Kirk and Kay Foreman for collecting the data; Oliver Zobay for his statistical advice; Professor George Browning for his advice and assistance with this study; and the reviewers for their comments on a previous version of this manuscript.

Contributors: WW and DM participated in the study design, supervised recruitment of participants and analysed the data. All authors drafted the manuscript and/or contributed to its revision, and approved the final version. DM is guarantor.

Funding: The Scottish section of the IHR is supported by intramural funding from the Medical Research Council (grant number U135097131) and the Chief Scientist Office of the Scottish Government.

Competing interests: All authors have completed the Unified Competing interest form at www.icmje.org/coi_disclosure.pdf (available on request from the corresponding author) and declare: no financial relationships with any organisations that might have an interest in the submitted work in the previous three years; no other relationships or activities that could appear to have influenced the submitted work.

Ethical approval: This study was approved by the West of Scotland research ethics service (WoS REC(4) 09/S0704/12). All participants gave informed consent.

Data sharing: No additional data available.

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Figure Legends:

Figure 1. Average level (dB SPL) for each digit across three sessions as a function of frequency for three whisperer groups (OE, OI & YI) showing ± 1 standard deviation. Clinic room noise superimposed to show possible masking effects.

~~*Figure 2. Flow of participants through experiment 2.*~~

Figure ~~3~~2. Mean percent correct over 15 simulated whispered voice test trials as a function of three-frequency pure-tone average (PTA) hearing loss for 112 individual ears tested with the recordings of 2 OE and 2 YI whisperers. Data points above the 50% threshold indicate a pass.

Figure ~~4~~3. ROC analysis for experienced and inexperienced whisperers, showing sensitivity as a function of false positive rate for each whisperer (separate panels). Points along the curve are labelled in 5 dB HL increments, and the total area under the curve (AUC) is given below the diagonal.

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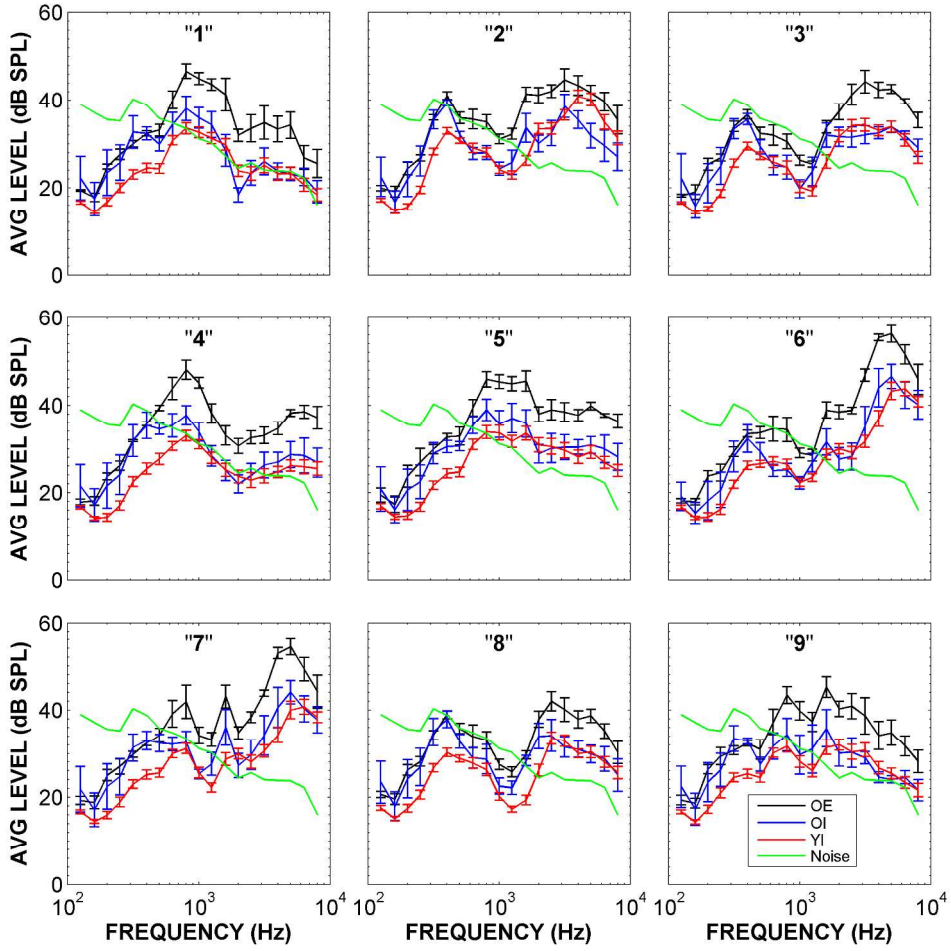

Figure 1. Average level (dB SPL) for each digit across three sessions as a function of frequency for three whisperer groups (OE, OI & YI) showing ± 1 standard deviation. Clinic room noise superimposed to show possible masking effects.
222x211mm (300 x 300 DPI)

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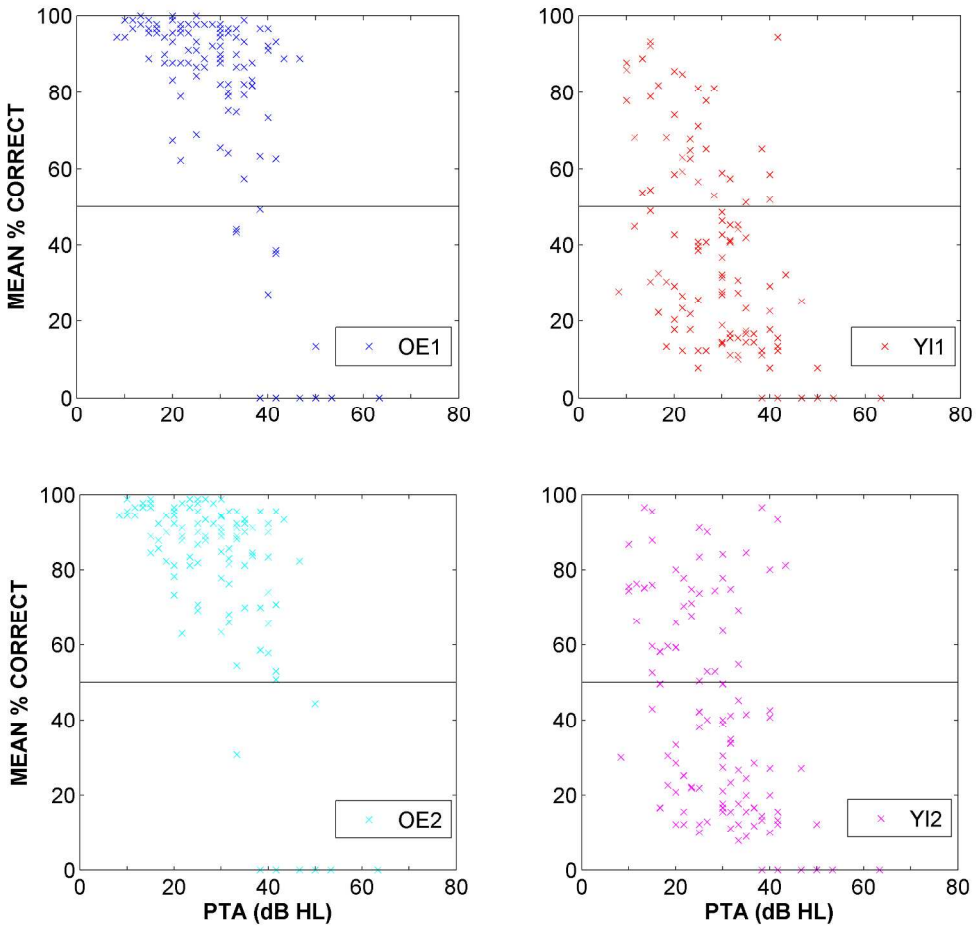

Figure 2. Mean percent correct over 15 simulated whispered voice test trials as a function of three-frequency pure-tone average (PTA) hearing loss for 112 individual ears tested with the recordings of 2 OE and 2 YI whisperers. Data points above the 50% threshold indicate a pass.
222x211mm (300 x 300 DPI)

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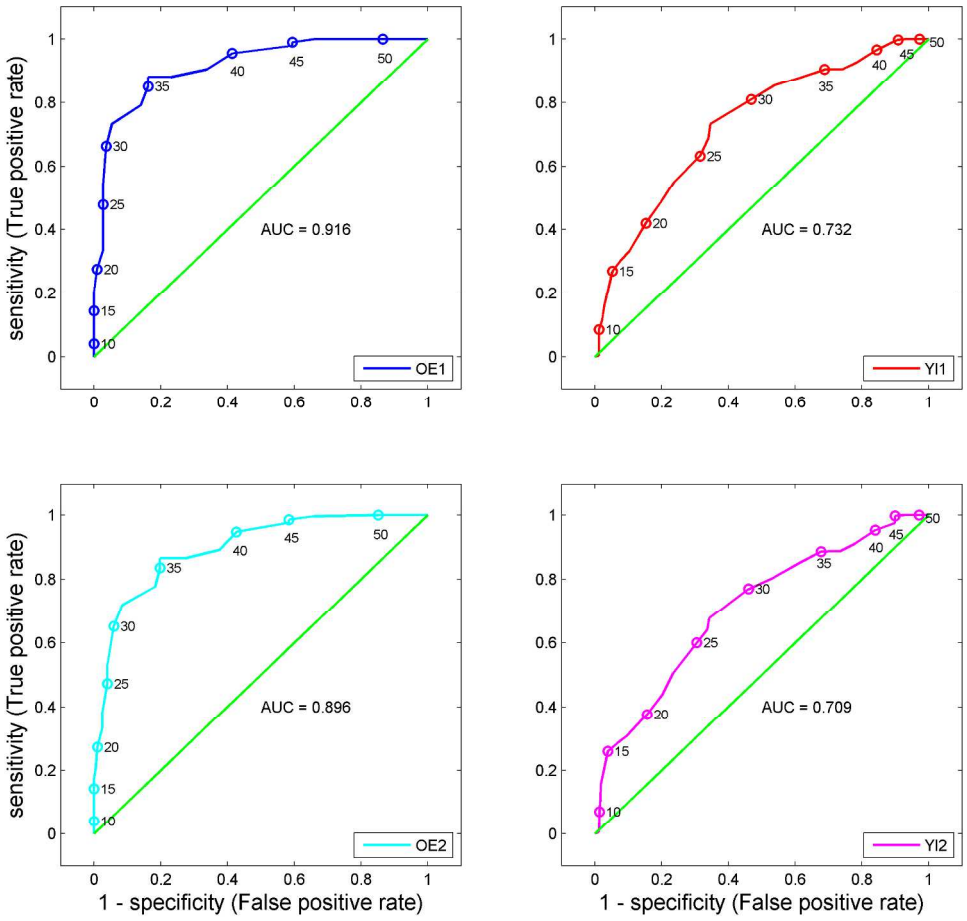

Figure 3. ROC analysis for experienced and inexperienced whisperers, showing sensitivity as a function of false positive rate for each whisperer (separate panels). Points along the curve are labelled in 5 dB HL increments, and the total area under the curve (AUC) is given below the diagonal.
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STARD checklist for reporting of studies of diagnostic accuracy

(version January 2003)

Section and Topic	Item #		On page #	
			Exp 1	Exp 2
TITLE/ABSTRACT/ KEYWORDS	1	Identify the article as a study of diagnostic accuracy (recommend MeSH heading 'sensitivity and specificity').	1	1
INTRODUCTION	2	State the research questions or study aims, such as estimating diagnostic accuracy or comparing accuracy between tests or across participant groups.	6	6
METHODS				
Participants	3	The study population: The inclusion and exclusion criteria, setting and locations where data were collected.	7	10
	4	Participant recruitment: Was recruitment based on presenting symptoms, results from previous tests, or the fact that the participants had received the index tests or the reference standard?	7	10
	5	Participant sampling: Was the study population a consecutive series of participants defined by the selection criteria in item 3 and 4? If not, specify how participants were further selected.	7	10
	6	Data collection: Was data collection planned before the index test and reference standard were performed (prospective study) or after (retrospective study)?	NA	10
Test methods	7	The reference standard and its rationale.	9	9
	8	Technical specifications of material and methods involved including how and when measurements were taken, and/or cite references for index tests and reference standard.	8	10
	9	Definition of and rationale for the units, cut-offs and/or categories of the results of the index tests and the reference standard.	NA	11
	10	The number, training and expertise of the persons executing and reading the index tests and the reference standard.	NA	11
	11	Whether or not the readers of the index tests and reference standard were blind (masked) to the results of the other test and describe any other clinical information available to the readers.	NA	11
Statistical methods	12	Methods for calculating or comparing measures of diagnostic accuracy, and the statistical methods used to quantify uncertainty (e.g. 95% confidence intervals).	NA	14/15
	13	Methods for calculating test reproducibility, if done.	NA	NA
RESULTS				
Participants	14	When study was performed, including beginning and end dates of recruitment.	7	14
	15	Clinical and demographic characteristics of the study population (at least information on age, gender, spectrum of presenting symptoms).	7	14
	16	The number of participants satisfying the criteria for inclusion who did or did not undergo the index tests and/or the reference standard; describe why participants failed to undergo either test (a flow diagram is strongly recommended).	7	14
Test results	17	Time-interval between the index tests and the reference standard, and any treatment administered in between.	NA	10
	18	Distribution of severity of disease (define criteria) in those with the target condition; other diagnoses in participants without the target condition.	NA	14
	19	A cross tabulation of the results of the index tests (including indeterminate and missing results) by the results of the reference standard; for continuous results, the distribution of the test results by the results of the reference standard.	NA	14
	20	Any adverse events from performing the index tests or the reference standard.	NA	NA
Estimates	21	Estimates of diagnostic accuracy and measures of statistical uncertainty (e.g. 95% confidence intervals).	NA	15/16
	22	How indeterminate results, missing data and outliers of the index tests were handled.	NA	NA
	23	Estimates of variability of diagnostic accuracy between subgroups of participants, readers or centers, if done.	NA	NA
	24	Estimates of test reproducibility, if done.	NA	NA
DISCUSSION	25	Discuss the clinical applicability of the study findings.	NA	19

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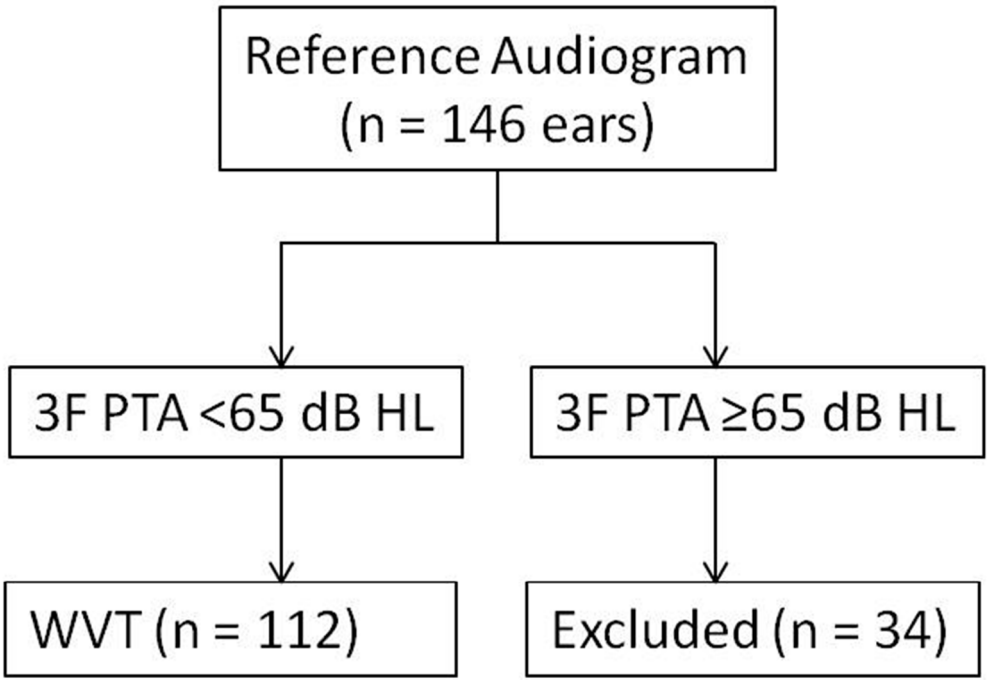

Flow of participants through experiment 2
110x75mm (150 x 150 DPI)

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