Do Purpose-Designed Auditory Tasks Measure General Speediness?

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ABSTRACT

This study was concerned with the measurement of General Speediness (Gs) using the auditory modality. Existing as well as purpose-developed auditory tasks that maintained the cognitive requirements of established visually presented Gs marker tests were completed by $N = 80$ university undergraduates. Analyses supported the results of our previous work [1] and auditory and visual tasks combined to define latent RT and Gs factors. Moreover, the analysis did not support the presence of modality-specific speed factors. Overall, this study provides further evidence suggesting that auditory tasks might successfully measure existing broad abilities defined in intelligence theories (*i.e.*, Gf, Gc, etc.) provided they maintain the same cognitive requirements as existing visual measures of such constructs.

Keywords: Auditory Intelligence; Auditory Abilities; Intelligence; Cognition; Speed of Processing

1. Introduction

The auditory perceptual domain is the second-most researched modality in the study of human intelligence [2]. Research has shown that auditory tasks combine to define a broad auditory perceptual factor (Ga) thought to exist at the second stratum of intelligence hierarchies—*i.e.*, Gf Gc theory [3]—alongside other broad constructs including fluid reasoning (Gf) and crystallized ability (Gc). Although the existence of this broad perceptual factor is relatively well replicated, our understanding of auditory abilities and how they relate to other broad cognitive constructs remains poor. According to Roberts, Pallier and Goff [4], conclusions regarding the auditory modality have been drawn on the basis of only a handful of data sets, none of which offers a satisfactory account of this modality.

Stankov [5] was the first to test the hypothesis that auditory tasks would define a broad Ga factor and empirically validated its presence and importance in intelligence theories. Carroll [6] noted however, that although the existence of Ga was indubitable, defining the domain of auditory abilities was difficult because there had been "no trustworthy or extensive factor-analytic studies of musical talent" (p. 364) and the majority of factor analytic studies of intelligence had "totally neglected the domain of auditory abilities" (p. 365). The need to distinguish between abilities that are and are not strictly auditory abilities was also stressed. In order to be considered an

auditory ability, Carroll (1993) requires there to be a reliance on the characteristics of the auditory stimulus and the ability to recognize and discriminate those characteristics. On the other hand, abilities such as speech comprehension rely on the knowledge of language structure and reliance on audition specifically is incidental. Speech comprehension might only be considered an auditory ability when the speech is distorted or manipulated, and in which case increased attention is devoted to the processing and discrimination of the incoming auditory stimuli.

These guidelines adopted by Carroll [6] for the classification of auditory abilities accord with the hierarchy of auditory processes discussed by Stankov [7]. This hierarchy incorporates three layers comprising sensory, perceptual and thinking processes, respectively. Abilities at the lowest, sensory level relate weakly with each other as well as to higher-order processes [8], and they relate weakly to abilities in other sensory modalities. Auditory hearing threshold is characteristic of this sensory level of the hierarchy. The second level encompasses abilities involved in making fine frequency and tonal discriminations, spatial discriminations and loudness discriminations. The highest level of the hierarchy encompasses abilities that are intellective in nature and not reliant on audition. Auditory abilities as envisaged by Carroll [6] are most characteristic of the perceptual level of the hierarchy, whereas more general abilities like speech comprehension reflect the highest, thinking level.

Stankov [7] suggests that mode of stimulus presentation at the highest level of the hierarchy is incidental and has proposed that such thinking abilities should be measurable via all modalities. These higher-order abilities are thought to rely on cognitively central yet complex mechanisms. Rather unfortunately, as highlighted by Roberts, Stankov, Pallier and Bradley [9], an implicit assumption of many extant theories of intelligence is that no knowledge of importance can be gained by employing tests of these complex abilities which utilize alternate modalities. Possibly as a result of this mindset, only a handful of studies have explored whether it is, in fact, possible to purposefully measure well established complex cognitive abilities—such as Gf and Gc etc.—via alternate modalities including audition, olfaction or tactile-kinesthesia.

One study of olfactory abilities [10] and two of tactile kinesthetic abilities [2,9] appear to have addressed this issue yet have provided somewhat mixed results. More specifically, Danthiir *et al*. [10] developed a single olfactory task for each of Gf, Gc, Short-term memory (SAR) and long-term memory (TSR) constructs. For the most part, these broad factors emerged from factor analysis of a test battery inclusive of validated visual marker tests but not all of the olfactory measures loaded as predicted. Only Olfactory Swaps and Multiple Choice Smell Identification loaded as hypothesised on Gf and Gc, respectively. Open Ended Smell Identification and Odor Memory did not load on Tertiary Storage and Retrieval (TSR) and Short Term Memory as expected (TSR did not emerge during factor analysis at all). On the other hand, Roberts *et al*.'s [9] and Stankov *et al*.'s [2] studies of tactile-kinesthetic abilities do suggest that tasks presented in these modalities can index constructs including Gf and broad visualization (Gv). Roberts *et al*. [9] proposed that the tactile-kinesthetic tasks in their study were cognitively complex and therefore they would relate to Gf and Gv more so than to Gc. Factor analysis of their data confirmed this: tactile-kinesthetic measures loaded on Gv rather than a modality specific factor. Stankov *et al*. [2] replicated this finding and reported that complex tactile-kinesthetic tasks were again difficult to differentiate from Gv. Interestingly, Stankov *et al*.'s study also included "cognitively simpler" (p. 25) tactile-kinesthetic tasks and these were found to define modality specific factors analogous to broad Ga.

When considering the auditory modality, there does not appear to have been any studies specifically concerned with the extent to which auditory tasks might index established constructs like Gf and Gc. Some of Stankov and Horn's studies [11-13] have found relationships between particular auditory tasks and broad second stratum constructs. For instance, listening verbal comprehension does appear to correlate moderately with Gc [12] and tonal series and chord series have been found to

relate to Gf [14]. In the case of tonal series and chord series, however, these tasks usually share more variance with broad Ga than Gf when sufficient auditory measures are present for Ga to be defined. This is not surprising given these latter tasks depend primarily on the ability to make tonal comparisons whilst listening comprehension relies on prior knowledge of language. Findings such as these appear to support Carroll's (1993) classification of auditory abilities noted above.

Other studies broadly concerned with auditory tasks provide limited data concerning the extent to which such tasks index predefined, existing constructs. For example, attempts have been made to measure an auditory inspecttion time (AIT) analogous to that measured by the vertical lines visual IT task [VIT; see 15]. A series of auditory Inspection Time (AIT) measures have been developed, based on pitch discrimination [16], loudness discrimination [17] and spatial localisation [18], respectively. As is the case with VIT, each of these measures has been shown to relate to performance on intelligence tests [19]. However, the pitch and loudness discrimination tasks do not appear to rely on the constructs underpinning VIT. Instead, they have been shown to relate to measures of fine perceptual resolution including pitch discrimination ability [see 20, for a discussion of these findings]. The spatial task relates more consistently with the intended VIT construct and other associated abilities [18,20], but it still shares considerable variance with the other AIT measures that is independent of its relationship to VIT [21]. Thus, despite the intention of measuring the IT indexed by VIT, the auditory tasks have generally not succeeded.

Overall, findings from tactile, olfactory and auditory research appear in some instances to challenge the notion that existing constructs can be measured via all modalities. The crux of Stankov's (1994) hypothesis, however, is that alternate tasks must maintain the cognitive requirements that underpin the ability/construct in question. Thus, although findings regarding AIT and olfactory measures do not entirely support this theory, there is a distinct possibility that this reflects inattention to this necessary detail. We have argued elsewhere [20] that the reason why pitch and loudness AIT tasks are unsuccessful measures of IT might be due to a disregard of the cognitive demands imposed by the VIT task. For example, pitch and loudness tasks are based on temporal discriminations whereas VIT and the putatively more successful spatial AIT task require spatial discriminations. On the other hand, complex tactile tasks which appear to rely on visualisation display consistent relationships with visual tasks that rely on this same ability. Similarly, listening verbal comprehension and speech comprehension, as already outlined, rely on prior knowledge of language and this underpins performance on visual measures of these abilities, hence their strong relationships.

Recently, Zajac and colleagues [1] considered the idea that broad cognitive abilities could be measured via different modalities by examining whether it was possible to purpose-develop auditory tasks to measure the specific, established broad cognitive ability, General Speediness (Gs). To achieve this, they compiled a battery of auditory tasks, some of which were developed so as to be analogous to existing visual Gs marker tests including Digit Symbol [22], Number Comparisons [23] and Findings As [24]. During task development the important characteristics of speed tasks were recognised and maintained. For example, it is particularly important that items be relatively easy to complete and that item difficulty be maintained within each task to ensure that performance reflects only the speed with which participants complete the items [see 6].

Zajac *et al.* [1] reported that the auditory and visual tasks in their test battery combined to define moderately related factors termed Reaction Time (RT) and Gs. RT was loaded on by the visual and auditory RT tasks whilst Gs subsumed the new auditory speed tasks. Zajac *et al.* [1] suggested that the latent factors might not reflect modality specific functions because both visual and auditory speed tasks loaded comparably and moderately on these factors. This would not be expected if modality specific processes underpinned these latent constructs.

Despite Zajac *et al.*'s [1] study providing some interesting preliminary data a number of limitations render them tentative only. In particular, although the auditory and visual tasks combined to define two related speed factors only three visual tasks had been measured as part of the test battery. Therefore, the visual modality was under-represented and this may have precluded the extraction of modality specific speed factors. The purpose of the present study then was to address this limitation. To achieve this aim, the study sought to assess performance on an increased number of visual Gs marker tests as well as the auditory tests previously designed [1]. Using factor analytic techniques, we could then examine the extent to which modality specific speed factors may underpin performance on the visual and auditory speed tasks in order to assess whether or not Gs is being reliably measured by the new auditory tasks.

2. Methods

2.1. Participants

Participants were $N = 80$ undergraduate psychology students of the University of Adelaide. There were $N = 53$ females and $N = 27$ males with a mean age of 21.0 years ($SD = 3.6$ years). All participated as part of their first year psychology course requirements.

2.2. Apparatus

The presentation of all tasks and recording of responses

was controlled by one of three identical Pentium 4 class computers. Visual stimuli were presented on 17 inch LCDs. Auditory stimuli were presented via Sony MDR-XD100 stereo headphones. All auditory tones were calibrated prior to the study using a Radio Shack 33-4050 Sound Level Meter.

2.3. Materials

2.3.1. Reaction Time Tasks

Simple Auditory Reaction Time (*ART*). To begin each trial, the participant pressed the number "5" key in the numeric keypad of the keyboard. After 300 ms a cue-tone (100 ms at 880 Hz) was presented followed, after a silent interval of variable duration (1300 ms, 1700 ms, 2100 ms or 2500 ms), by the target tone; a 500 ms "bell" sound centered on a frequency of 800 Hz. Participants lifted their finger off the number "5" key and pressed the number "8" key as quickly and as accurately as possible. Participants were required to complete 10 correct trials out of 10 before they proceeded to the test. The outcome measure was mean RT-time between on-set of target and pressing of response key—calculated after the removal of outliers (± 3 SD) and errors.

Two-Choice Auditory Reaction Time (*ART₂*). The target tone in this task was presented to the left or right ear only. Participants responded by pressing the number '4' key if the target tone was played to the left ear, or number "6" if it was played to the right ear. All other aspects of the task were identical to ART.

Three-Choice Auditory Reaction Time (*ART₃*). During this task the target tone was presented to the left ear only, both ears, or right ear only. Participants responded by pressing the number "4" key in the numeric keypad for the left ear, number "8" if it was played to both ears, or number "6" for the right ear. All other aspects of the task were identical to ART.

Visual Reaction Time (*VRT*). This task was functionally equivalent to ART but required participants to respond upon the illumination of an empty circle, 4 cm in diameter, presented against the black background of the computer screen. The white outline of the circle was presented at the onset of each trial and acted as a cue, and the circle illuminated red after a variable duration of 1300 ms, 1700 ms, 2100 ms, or 2500 ms.

Two-Choice Visual Reaction Time (*VRT₂*). This task was the same as VRT but used two circles presented side by side, and with a space of 12 mm between them. Participants responded by pressing the number "4" key if the left circle illuminated, or the number "6" key if it was the right circle.

Three-Choice Visual Reaction Time (*VRT₃*). This task utilized three circles presented side by side, and with a space of 12 mm between them. Participants responded by pressing the number "4" key if the left circle illuminated

red, the number "8" key if the centre circle illuminated, or the number "6" key if it was the right circle.

2.3.2. Speed of Processing Tasks

Symbol Digit (*SD*). A computerised coding task was employed as a measure of Gs [see 22]. A code table was presented at the top of the computer screen throughout the task. This comprised nine symbols arranged horizontally, to which nine digits, presented directly beneath them, were paired. For each item, one symbol was presented in the centre of the computer screen and participants responded by left clicking the mouse on its corresponding digit in a 3×3 numerical grid positioned at the bottom of the screen. Subsequent items did not commence until a correct response was registered. Participants were required to complete two practice trials correctly before they proceeded to the test. The outcome measure was the number of items correctly completed in 2 minutes.

Audio Code (*AC*). This task was developed to be an auditory analogue of the symbol digit task described above. A code table is displayed at the top of the computer screen for the duration of the task, comprising of pictures of eight musical instruments arranged horizontally, to which one of the numbers one through eight was paired. The instruments include a snare drum, trumpet, guitar, cymbals, piano, bell, harp and violin. For each item, the sound of one of the instruments was presented via headphones at an intensity of 65 db. Participants responded by left clicking the mouse on its corresponding digit in a 2 x 4 numerical response grid positioned at the bottom of the screen. Subsequent items commenced after a response was registered. Participants completed two familiarization phases: in the first, instrument names were presented and participants clicked on the corresponding instrument (2 trials each); in the second, instrument sounds were presented instead of text (2 trials each). Following this, participants were required to complete four test trials for each instrument correctly before they could proceed to the test phase. The outcome measure was the number of items correctly completed in 2 minutes.

Chasing Digits Visual (*CD$_v$*). This was designed to be similar to the Digit-Digit task used by McPherson and Burns [22], which was found to share substantial variance with Gs marker tests. It incorporated a 3×3 numerical response grid positioned in the centre of the computer screen against a black background. For each item, one of the digits one through nine illuminated green; trial order was pseudo-randomised with the restriction that no digit could be presented successively. The participants responded as quickly and accurately as possible by left clicking the mouse on the corresponding number in the response grid. Subsequent items commenced 200

ms following the response. Participants were required to complete ten correct trials out of ten before they proceeded to the test. The outcome measure was the number of items correctly completed in 1 minute.

Chasing Digits Auditory (*CD$_a$*). This task was developed to be an auditory analogue of, and was functionally equivalent to, CD$_v$. However, for each item one of the digits one through nine was presented auditorily to participants via headphones at an intensity of 65 dB. To respond, participants clicked the corresponding number in the response grid.

Number Comparisons (*NC*). This task was based on the test with the same name, from the ETS Factor Reference Kit [23]. Trials consisted of two digit-strings of equal length (3 to 12 digits long) presented side by side and with a 6 cm space between them. Participants clicked the on-screen response button "Yes", if they thought the strings were identical, or "No" if they were different. Participants were required to complete five correct trials out of five before they proceeded to the test. The outcome measure was the number of items correctly completed in 90 seconds.

Tone Comparisons (*TC*). This task was developed to be an auditory analogue of NC and was functionally equivalent to it. Trials consisted of two sequentially presented tones which were identical, or differed by either a semi-tone or tone. Tones were presented at intensity of 65 dB and participants clicked the on-screen response button "Yes", if they thought the tones were identical, or "No" if they were different.

Finding As (*FA$_s$*). There exist numerous variations of this search task [24,25]. In this version, stimuli were two nouns, five to eight letters in length. All words had a concreteness-of-imagery value of 600 or over, on a scale ranging from 100 to 700: the lowest value indicated maximum abstractness and the highest maximum concreteness. Fifteen of the 60 words contained the letter A. Words were presented pseudorandomly—one at a time—and participants were to press the onscreen button "yes", if the word contained an "A" and the "no" key if it did not. Participants were required to complete five correct trials out of five before they proceeded to the test, and practice trials used different stimuli to the test phase. The outcome measure was the number of items correctly completed in 90 seconds.

Hearing As (*HA$_s$*). This task was an auditory version of Finding As and was functionally equivalent. In this version, stimuli were nouns, five to eight letters in length. All words again had concreteness-of-imagery values of 600 or over. Fifteen of the 60 words contained the letter "A" and all of these used the long vowel pronunciation. The purpose of this was to reduce any potential spelling confound that might occur for the short vowel sound—where the pronunciation of the "A" is not as distinct—or

in the case of silent "A". Participants were informed of this restriction.

Visual Inspection Time (VIT). The vertical lines inspection time task was used to estimate VIT. Stimuli were presented on a video monitor at a viewing distance of approximately 60 cm. Preceding the target figure was a warning cue of approximately 520 ms; the cue was a small white plus (+) sign measuring 6×6 mm, presented in the centre of the computer screen. The target figure consisted of two vertical lines; one measured 15 mm and the other 30 mm. These were joined at the top by a horizontal line of approximately 18 mm. A "flash mask" [26] of 375 ms immediately replaced the target figure and consisted of two vertical lines 35 mm in length, shaped as lightning bolts. The shorter line appeared on either side of the target figure equiprobably. Participants indicated on which side the short line appeared by clicking either the left or right mouse button, respectively.

2.4. Procedure

Upon arriving at the testing session participants were seated in a cubicle in a quiet laboratory and they were guided through the test battery automatically by the computer. Detailed instructions and practice phases were presented prior to the onset of each task, and the first author was present to answer any questions. Participants completed the tasks in the following order: VRT; VRT$_2$; VRT$_3$; ART; ART$_2$; ART$_3$; CD$_A$; CD$_V$; SD; AC; HA$_S$; FA$_S$; TC; SC; and VIT. Simple and two-choice RT tasks consisted of 32 trials whilst the three-choice tasks consisted of 36 trials.

For the VIT task, the instructions emphasised accuracy rather than speed of responding. Practice trials required 10 correct trials out of 10 with SOA of approximately 835 ms; 10 correct trials out of 10 with SOA approximately 420 ms; and nine correct trials out of 10 with SOA approximately 250 ms. The estimation process began with SOA approximately 250 ms and followed an adaptive staircase algorithm [27]. The average SOA was calculated over eight reversals of direction on the staircase, giving an estimate of the SOA with an associated probability of 79% of making a correct response.

2.5. Data Preparation

Outliers (± 3 SD) and errors were removed from individual RT data files and the average number of trials used to calculate RT scores was: ART ($M = 31.2$, $SD = 1.0$); ART$_2$ ($M = 31.2$, $SD = 0.9$); ART$_3$ ($M = 34.5$, $SD = 1.3$); VRT ($M = 31.2$, $SD = 0.6$); VRT$_2$ ($M = 31.4$, $SD = 0.6$); and VRT$_3$ ($M = 35.0$, $SD = 0.9$). Following this the data for all tasks were collated and assessed for outliers (*i.e.*, ± 3 SD) and missing values. No missing values were present, but 7 outliers were found randomly distributed

across six variables. These values were replaced using the Expectation Maximization (EM) imputation procedure in SPSS v.17.

3. Results

Table 1 presents descriptive statistics for all measures and split half reliability estimates for APM and the speed measures. As can be seen, all reliabilities are acceptable. Regarding means, it is interesting to note that simple ARTs are faster than for VRT [$t(79) = 5.99$, $p < 0.001$] yet this pattern alters as the number of alternatives increases, with VRT$_3$ performance becoming better than for ART$_3$ [$t(79) = 9.99$, $p < 0.001$]. Furthermore, for the Gs tasks, the number of completed items is generally higher for the visually presented tasks except for NC, where the average is lower than for TC.

Presented in **Table 2** are the correlations between the tasks. As expected, the RT tasks relate moderate to strong with each other, suggesting they all tap a similar construct. The Gs measures correlate well with one another also and the auditory measures correlate well with their visual analogues except for NC and TC, which do not correlate significantly. This may partly reflect differences in the complexities of these tasks, which would also explain the marked difference between the average numbers of items completed in each, as already noted.

Table 1. Descriptive statistics and split-half reliabilities for all cognitive tests.

	M	*SD*	Split-Half
ART	274.0	62.2	0.88
VRT	304.3	46.1	0.89
ART$_2$	368.0	73.3	0.90
VRT$_2$	360.6	45.0	0.90
ART$_3$	505.0	91.1	0.90
VRT$_3$	424.5	52.5	0.81
VIT[a]	46.9	11.2	-
CD$_A$	65.1	4.4	0.71
CD$_V$	89.0	6.6	0.92
FA$_S$	55.7	5.9	0.73
HA$_S$	43.5	6.7	0.84
NC	24.7	4.2	0.67
TC	53.1	4.7	0.81
AC	68.7	10.4	0.79
SD	92.8	15.5	0.80

RT & IT = Msec; All else = N correct; [a]Split-half reliability not available due to the format of this task. CD$_A$, SD, AC, TC, HA$_S$ = items. All else = msec. ART, Simple Auditory Reaction Time; VRT, Visual Reaction Time; ART$_2$, Two-Choice Auditory Reaction Time; VRT$_2$, Two-Choice Visual Reaction Time; ART$_3$, Three-Choice Auditory Reaction Time; VRT$_3$, Three-Choice Visual Reaction Time; VIT, Visual Inspection Time; CD$_A$, Chasing Digits Auditory; CD$_V$, Chasing Digits Visual; FA$_S$, Finding As; HA$_S$, Hearing As; NC, Number Comparisons; TC, Tone Comparisons; AC, Audio Code; SD, Symbol Digit.

Table 2. Correlations between cognitive tests.

	ART	VRT	ART$_2$	VRT$_2$	ART$_3$	VRT$_3$	VIT	CD$_A$	CD$_V$	FA$_S$	HA$_S$	NC	TC	AC
VRT	0.69**													
ART$_2$	0.52**	0.32**												
VRT$_2$	0.43**	0.65**	0.53**											
ART$_3$	0.46**	0.28*	0.77**	0.38**										
VRT$_3$	0.25*	0.37**	0.49**	0.61**	0.61**									
VIT	-0.19	0.01	-0.03	0.10	0.01	0.26*								
CD$_A$	-0.06	-0.21	-0.27*	-0.26*	-0.34**	-0.49**	-0.21							
CD$_V$	-0.09	-0.15	-0.37**	-0.34**	-0.43**	-0.59**	-0.30**	0.68**						
FA$_S$	0.09	-0.10	-0.12	-0.07	-0.22	-0.30**	-0.23*	0.52**	0.49**					
HA$_S$	-0.03	-0.05	-0.16	-0.08	-0.32**	-0.30**	-0.25*	0.20	0.16	0.43**				
NC	0.18	-0.06	0.07	-0.08	-0.05	-0.20	-0.36**	0.40**	0.32**	0.53**	0.10			
TC	-0.02	-0.21	-0.28*	-0.41**	-0.37**	-0.54**	-0.27*	0.33**	0.35**	0.15	0.38**	0.18		
AC	0.11	0.04	-0.11	-0.14	-0.14	-0.40**	-0.16	0.35**	0.32**	0.33**	0.24*	0.34**	0.40**	
SD	0.10	-0.11	-0.05	-0.17	-0.06	-0.33**	-0.20	0.41**	0.45**	0.40**	0.06	0.50**	0.21	0.44**

**Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed). ART, Simple Auditory Reaction Time; VRT, Visual Reaction Time; ART$_2$, Two-Choice Auditory Reaction Time; VRT$_2$, Two-Choice Visual Reaction Time; ART$_3$, Three-Choice Auditory Reaction Time; VRT$_3$, Three-Choice Visual Reaction Time; VIT, Visual Inspection Time; CD$_A$, Chasing Digits Auditory; CD$_V$, Chasing Digits Visual; FA$_S$, Finding As; HA$_S$, Hearing As; NC, Number Comparisons; TC, Tone Comparisons; AC, Audio Code; SD, Symbol Digit.

In order to explore the latent factors underpinning performance across the speed tasks, we generated eigenvalues and a scree plot using principle components analysis. There were four components with eigenvalues greater than 1, accounting for 33.3%, 18.5%, 8.4% and 7.1% of the variance, respectively. Inspection of the scree plot suggested, however, that there were two dominant factors and possibly a third, with the scree commencing after this. Therefore, we performed exploratory structural equation modeling using maximum likelihood (ML) estimation in MPlus version 5.0 [2]. We modeled three related factors and allowed the tasks to load freely across them. The model terminated but the residual covariance matrix was not positive definite due to VRT having a loading of $r = 1.30$ on a factor that was otherwise unrelated to the remaining visual and auditory tasks (average loading of $r = 0.07$). Therefore, we decided to remove VRT from subsequent models as well as ART, given it was its auditory analogue. We also reduced the number of latent factors to two given the third was clearly defined by VRT only.

Following these modifications the model was re-estimated and it terminated successfully. The fit of the model was considered quite acceptable given that no paths were constrained [$\chi^2(53) = 115.66$, $p < 0.001$; CFI = 0.84; RMSEA = 0.12; SRMR = 0.06], resulting in a large number of near zero factor loadings. The first factor was identified as an RT factor having strong loadings from both visual and auditory RT tasks, and weak but significant loadings from CD$_A$, CD$_V$ and TC. The second factor was interpreted as a Gs factor, defined by generally moderate loadings from the other tasks, and with a weak loading

from VRT$_3$. The correlation between the latent factors was weak but significant ($r = –0.31$, $p = 0.01$).

We modified this two factor model by constraining the non-significant paths to zero. Then, based on statistical significance of loadings and modification indices the model went through several permutations to achieve adequate fit. The final model is presented as **Figure 1** and as can be seen the two factors of RT and Gs remain distinct and the fit of the model is adequate [$\chi^2(60) = 93.44$, $p = 0.003$; CFI = 0.92; RMSEA = 0.08; SRMR = 0.08]. It was possible to achieve better fit through correlating the residuals of RT measures and other auditory/visual pairs (e.g., SD and AC), but in the interest of parsimony we chose this more restrictive model. The one discrepancy noted is that although TC was envisaged as a marker of Gs, it was better placed as an indicator of the RT factor as it shared more variance with this latent construct.

Although the factors resulting from ESEM herein conform well to those found in our earlier paper [1] we chose to specifically test the possibility of modality specific speed factors using confirmatory modeling. We altered the model shown in **Figure 1** to include four latent variables: auditory RT, visual RT, auditory Gs and visual Gs. We also allowed TC to define auditory Gs rather than auditory RT given it was developed to be an auditory analogue of NC.

This model terminated normally [$\chi^2(84) = 238.14$, $p < 0.001$; CFI = 0.69; RMSEA = 0.15; SRMR = 0.11]. However, fit was poor due to the latent variable residual covariance matrix not being positive definite. This issue was traced to a perfect linear dependency between visual
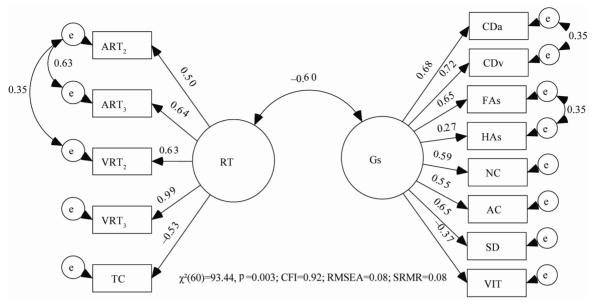
Figure 1. Latent structure of auditory and visual speed tasks.

Gs and auditory Gs ($r = 1.09$). Therefore, we modified the model to include only modality specific RT factors, and a single latent Gs defined by tasks of both modalities. This subsequent model terminated successfully and all tasks loaded moderately and significantly on their respective factors. Moreover, the relationship between latent factors RT_A and RT_V was significant and strong ($r = 0.74$), and the relationship of Gs to each of these factors was moderate and significant also ($r = 0.42$ and $r = 0.67$, respectively). The fit of this model, however, was again not adequate [$\chi^2(87) = 242.99$, $p < 0.001$; CFI = 0.69; RMSEA = 0.15; SRMR = 0.11]. Short of correlating the residuals of most indicator variables, we could not get this model to fit adequately. Thus, this analysis generally supports the model shown in **Figure 1** because adequate fit is only obtained when latent auditory and visual RT factors are combined.

4. Discussions

The purpose of the present study was to replicate and extend the findings of our earlier research concerning whether broad Gs could be measured auditorily [1]. The same purpose-developed auditory tasks were employed again and in line with our previous findings we expected to find relationships between the visual and auditory Gs tasks. Furthermore, by including more visually presented tasks in this study we sought to establish whether their absence precluded the identification of modality-specific latent speed constructs.

Overall, findings from the present study support those of our earlier investigation. The auditory tasks generally correlated well with their visual analogues except for Tone Comparisons (TC) and Number Comparisons (NC),

which correlated weakly. It is probable that this finding reflects the marked differences in the difficulty of each of these tasks. Whilst TC involves a comparison of two relatively simple successive stimuli (single tones of different frequency) the stimuli in NC are complex, involving up to 12 digits in each. Thus, comparing the two digit strings is arguably more complex than comparing two simple tones. It would be interesting to correlate performance on TC and NC inclusive only of the simpler three-digit strings. Unfortunately, given the format of our tests our data do not allow this.

The inclusion of more visual marker tests in this study has answered an important question. Specifically, we were concerned that the dominance of auditory tasks in the previous study [1] may have prevented the appearance of distinct auditory and visual speed factors. In contrast to our earlier study in which we tested confirmatory structural models based on a-priori hypotheses, we this time undertook exploratory analysis in order to allow the latent factors to be naturally defined. This distinction is important because with CFA several different factorial solutions can achieve acceptable fit yet not adequately represent the latent structure. Despite the differences in approach between the analyses herein and that used previously [1], the models derived in both studies are generally congruent. Distinct Gs and RT factors emerged again in the present study and they were moderately related, sharing about 36% of their variance.

The inclusion of more visual marker tests allowed us to explore whether specific modality speed factors could be extracted from the data. In the case of Gs, there appears some evidence that it does not distinguish between the auditory and visual modalities at least for the tasks

employed herein. If this were the case, then these modality factors should have emerged naturally in the exploratory analysis undertaken. Restricting auditory and visual tasks to define modality specific Gs factors using confirmatory modeling provides further support for their absence. The correlation between latent visual and auditory Gs was $r = 1.09$ demonstrating their perfect linear dependence. Evidence for a single latent RT factor is less convincing because it was possible to define distinct auditory and visual RT factors. However, it was not possible to achieve adequate fit statistics for this model without correlating most residuals—with many resulting correlations not being theoretically sensible—and the resulting model would certainly not have been parsimonious. Moreover, the correlation between the modality specific factors was high ($r = 0.74$) and they shared approximately 55% of their variance. It can be concluded at this time that it is at least possible that there exists distinct auditory and visual RT factors, but that they are strongly related.

This and our previous [1] study fill an important gap in intelligence research. We have sought to test Stankov's [7] hypothesis that higher-order thinking abilities, otherwise referred to as broad cognitive abilities, can be indexed regardless of stimulus modality. Until now, this hypothesis had not been explicitly tested from an auditory perspective. However, it appears that broad Gs can be measured via both visual and auditory pathways and this has been replicated twice-over. Additionally, despite allowing for modality specific speed factors in our present analysis and study design, we do not find evidence to support this notion.

As Roberts *et al*. [9] have noted, an implicit assumption of modern intelligence theories is that no knowledge of importance can be gained through employing tests of complex abilities which utilise alternate modalities. Indeed this might be the case, and we have found no evidence that latent Gs as measured by visual and auditory tasks respectively, differs. However, regardless of whether more information is gained by broadening intelligence models and subsequently intelligence tests to encompass measurement of complex abilities via alternate modalities, it is the case that in doing so the measurement of cognition itself becomes more ecologically valid. People touch, smell, listen and visualise their environment. The persistent neglect of alternate modalities needs to be overcome and intelligence measures should be broadened to include multiple modalities. Only when this happens can we claim to have achieved 'truly balanced' measures of intelligence [29].

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