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Development and preliminary evaluation of a processing speed test for school-aged children utilizing auditory stimuli

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Abstract

The purpose of this pilot study was to develop and evaluate a test of processing speed that utilizes verbal stimuli - the Auditory Processing Speed Test (A-PST). Participants were 174 school children aged 6 to 12 years, who were required to respond to verbally-presented target stimuli and ignore foils. Inter-stimulus interval was adjusted adaptively. Younger children had significantly slower average processing speed (APS) than older children ($p < 0.0000001$, range 39 to 59 words per minute (wpm)). For each one year increase in age, processing speed increased by 4 wpm. Reaction time did not limit performance on the A-PST. However, impulsivity was a significant predictor of processing speed, with each 1 standard deviation (SD) increase in impulsivity resulting in a 0.47 SD increase in APS in wpm. Changes to the adaptive procedure of the A-PST to resolve the impact of impulsivity are discussed together with directions for future research.

Keywords: Auditory processing speed; Reaction time; Impulsivity

Abbreviations

ANOVA: Analysis of variance; A-PST: Auditory processing Speed Test; APS: Average processing speed; FH: Family history; ISI: Inter-stimulus interval; Ms: Milliseconds; RAP: Rapid auditory processing; RMS: Root mean square; RT: Reaction time; SD: Standard deviation; SLI: Specific language impairment; SEM: Standard error of measurement; Wpm: Words per minute

Introduction

Processing speed is the rate at which a person performs simple perceptual or cognitive tasks with reasonable accuracy [1]. Processing speed measures include a variety of tasks, including associating numbers with symbols, searching for and responding to specific targets, and rapid naming of visual stimuli [1]. Individual differences in processing speed have been shown to influence academic performance in the classroom [2]. Processing speed underlies many cognitive skills including reading word recognition, reading comprehension, verbal ability, and verbal reasoning [3]. As such, tests that assess processing speed may be important tools to identify children at risk of academic underachievement in the classroom. Early detection and subsequent management of deficits in these areas may allow children to reach their full scholastic potential and avoid issues commonly associated with poor learning outcomes, such as low self-esteem.

In a study of 214 children and adults aged 7 to 19 years [4], it was found that even when age-related differences in visual processing speed, working memory, and fluid intelligence were statistically controlled, individual differences in processing speed had a direct effect on working memory capacity, which, in turn, was a direct determinant of individual differences in fluid intelligence.

In a discussion on age-related aspects of auditory processing speed ability, it was reported that comprehension of spoken language declines more rapidly for older adults than for younger adults as speech rate increases [5]. However, the authors suggest that the auditory pathways of older adults are less able to process the distorted consonant phonemes that result from time compression techniques used to speed speech. To this end it was found that when speech is speeded in a way that minimizes the adverse effects of speed-induced acoustic distortions, increased rate of speech had the same effect on spoken language comprehension in younger and older adults [6].

Twenty school-aged children with specific language impairment (SLI) took part in a study which investigated whether a reduced speech input rate could enhance real-time language processing [7]. A word recognition reaction time task was used whereby participants monitored simple sentences for a target word and made a timed response immediately upon recognizing the target. Sentences were presented at normal speaking rate (approximately 4.4 syllables per second), a slow rate (time expanded by 25 per cent) and a fast rate (time compressed by 25 per cent). Results were compared to 20 age-matched typically developing (TD) children. The SLI group had significantly slower reactions times than the controls for the normal- and fast-rate sentences, but faster reaction times for slow-rate sentences. Within-group analyses showed that the children with SLI produced the fastest reaction times for slow-rate sentences and the slowest reaction times for fast-rate sentences. In comparison, the controls showed the fastest reaction times for fast-rate sentences and the slowest reaction times for slow-rate sentences. Age also had a significant effect. Regardless of language status, older children produced faster reaction times than younger children. Interestingly, even the oldest children with SLI still demonstrated significantly slower reaction times than the youngest TD children on the normal- and fast-rate sentences. The author concluded that the language processing of children with SLI can be enhanced by presenting material at a slower rate, as the rate of processing allows such children time to allocate their attentional resources more effectively to the various processing operations supporting comprehension.

A method for establishing individual fine-grained rapid auditory processing (RAP) thresholds in infants was developed using a tone-detection task [2]. Two groups of infants were studied, one with a positive family history (FH+) for specific language impairment (SLI) and one without (FH–). The infants listened to a repeating tone sequence (low–low) and were operantly trained to make a head turn when a different sequence (low–high) was detected. The tones were 70-msec in duration and were separated by a 500-msec silent inter-stimulus interval (ISI). Once the infant had learned this task to criterion, the ISI between tones was systematically decreased for correct responses or increased for incorrect responses, until an individual RAP threshold was established for each infant.

A highly significant difference in RAP thresholds was found between the FH+ and FH– infant groups. RAP thresholds were also the single best predictor of language outcomes at two years of age based on a large battery of sensory, perceptual and cognitive measures. By three years of age, two variables — RAP thresholds obtained at 6 months and male gender — together predicted 39–41% of the variance in language outcome. Furthermore, these two infant variables accurately classified 91.4% of three-year-old children who scored in the 'impaired' range on the Verbal Reasoning scale of the Stanford–Binet intelligence scales [8]. None of the infant variables could discriminate between three-year-old children on the non-verbal portions of the Stanford–Binet, demonstrating the specificity of the relationship between individual differences in infant RAP thresholds and subsequent individual differences in language and verbal intelligence.

However, longitudinal studies have demonstrated that many children who exhibit RAP deficits early in life do not demonstrate RAP deficits later in life [2]. It was uncertain if the deficits subsequently resolved, or whether RAP deficits become more difficult to assess using behavioural techniques due to the age-appropriateness of the stimuli and tasks that were used. Further, in order to measure pure processing speed, tasks must place minimal demand on working memory. That is, if the task requires that memory representations need to be maintained in the face of concurrent processing, working memory capacity is tapped as well as speed [9].

The majority of information presented in the classroom is auditory in nature. However, tests of processing speed typically administered to school children employ visually-presented materials, such as cancellation and pattern matching, and form part of a lengthy cognitive test battery such as the Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV) [10]. To this end, the primary aim of the present this pilot study was to design, develop and evaluate a test of processing speed that was auditory-specific. Further, the test was to be adaptive, fast to administer, completely computer generated, with automated scoring functions. The adaptive nature of the test design ensures that processing speed thresholds were determined quickly and accurately whilst avoiding floor and ceiling effects.

The test developed for the study, the Auditory Processing Speed test (A-PST), uses a word identification/categorization task whereby the inter-stimulus-interval (ISI) varies adaptively, resulting in a processing speed score measured in words-per-minute. In comparison to the RAP [2], it is hypothesized that the more "linguistically-loaded" A-PST task will be a more sensitive and ecologically valid behavioural measure of auditory processing speed in school-aged children. In line with previous recommendations [6], an adaptive procedure is utilized whereby the ISI between presented words is varied but the stimulus length maintained. In this way listener inability to process phoneme distortion will not impact on performance. Stimulus familiarization and instructions are computerized and the listener response is recorded by mouse click, so the entire test is fully automated. The development of the A-PST is fully described in the methods section.

Finally, the study aimed to determine whether processing speed for auditory stimuli improved with age; whether auditory processing speed was correlated with reaction time, and whether reaction time limited processing speed on the A-PST; and how processing speed was impacted by impulsivity (measured as false positives divided by true positives).

Method

Approval for the study was granted from the Australian Hearing Human Research Ethics Committee and the Catholic Schools Office, Diocese of Broken Bay.

Participants

Participants were recruited from a Catholic primary school in New South Wales, Australia, with an average Index of Community Socio-Educational Advantage value similar to the national average. Children in Years 1 to 6 took part in the study. Information letters and consent forms were distributed to parents or caregivers via the class teacher. Parents were advised that their child would be unable to take part in the study if English was not his or her first language or if there is a history of attention disorders (ADD or ADHD) or if a hearing problem was detected. Parents were advised that they would be contacted in writing if a hearing problem was identified, with suggestions provided for follow-up care. Written parental consent was obtained for all participants. Prior to testing, all children were given a brief verbal explanation of the nature of the study. It was made clear at the commencement of the test session that he or she could withdraw from the study at any time without having to give a reason, and there would be no penalty for doing so. Each participant was then asked if he or she was happy to proceed before any testing is initiated.

Grade	Number of Participants	Minimum (yrs; mths)	Maximum (yrs; mths)
1	22	6; 9	7; 5
2	34	7; 5	8; 5
3	32	8; 3	9; 4
4	35	9; 3	10; 5
5	25	10; 5	11; 6
6	27	11; 3	12; 6

Table 1: Number of participants and age range for all participants from Grades 1 to 6.

Data were collected from a total of 174 children aged between 6;9 [years; months] and 12;6 (mean 9;5). Participant numbers and age

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ranges for each grade are provided in Table 1. There were 99 males and 75 females. All participants had English as a first language, no ADD/ADHD, and pure tone thresholds ≤20 dB HL at octave frequencies between 500 to 8000 Hz.

Procedure

Testing was carried out in a quiet room in the participating school between 9 am and 3 pm. Testing took approximately 15 minutes per child.

Materials

Pure Tone Audiometry: Pure tone audiometric screening was performed using an Interacoustics Audio Traveller A222 portable audiometer with Telephonics TDH 39P audiometric headphones in H7A Peltor cups.

A-PST: Following audiometric testing the participants were evaluated on the A-PST. The A-PST graphical user interfaces and signal processing application programs were designed by the first author and developed in the C# programming language by a commercial software development company. The test was designed to be administered on a personal computer over headphones. The main menu screen takes the user through a series of steps. First, client data is entered by the administrator. The child then sets the output volume, as described in the section on calibration which follows.

The child's task is to use the computer mouse to click on a square displayed on the computer screen (response box) when he or she hears a number (one, two, three, four or five). The child must ignore any of the 15 monosyllabic nouns which are included as foils. An image of the A-PST test screen is provided as Figure 1. Before undertaking the actual test, the child must complete an automated word familiarization task whereby he or she is required to demonstrate they can identify each target and foil by using the computer mouse to match the word, which was presented over the headphones, to one of four images which appear on the computer screen (Figure 2).

In order to minimize the input required from the test administrator, instructional videos are included explaining how to complete the word familiarization task as well as how to complete the test itself. The pre-recorded instructions that are presented as part of the instructional videos are provided as Appendix A. A number of children in Years 1 and 2 experienced difficulty understanding the recorded instructions due to reasons discussed in the Discussion section. As such, the instructions for the familiarization task and the test itself were presented verbally by the examiners to these groups.

Target stimuli are five monosyllabic digits – one, two, three, four, five. According to the Wechsler Individual Achievement Test – Second Edition (Wechsler, 2002), children have the ability to discriminate numbers and to count to eight by age 5 to 6. Non-target stimuli (foils) are fifteen monosyllabic nouns from the semantic categories of animals (dog, cat, bear, pig, hen); body parts (hand, foot, knee, toe, leg); and small household items (spoon, cup, dish, plate, knife). All non-target semantic items were taken from The MacArthur-Bates Communicative Development Inventories [11] and are acquired by normally developing children aged 30 months of age. The targets and foils were selected from different semantic categories to avoid lexical neighbourhood effects influencing detection.

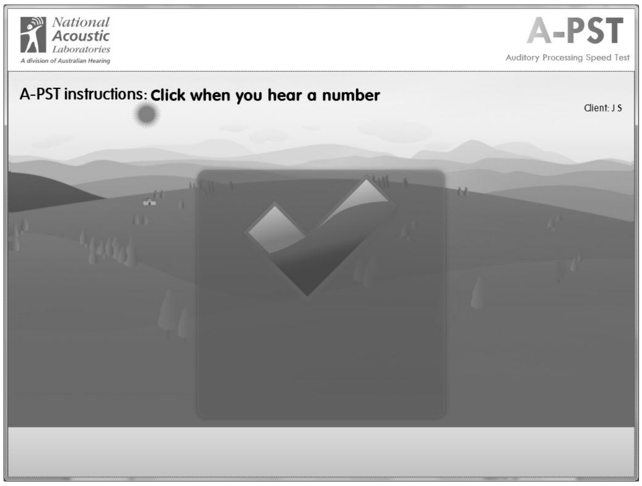

Figure 1: Auditory Processing Speed Test (A-PST) test screen showing positive reinforcement for correct response.

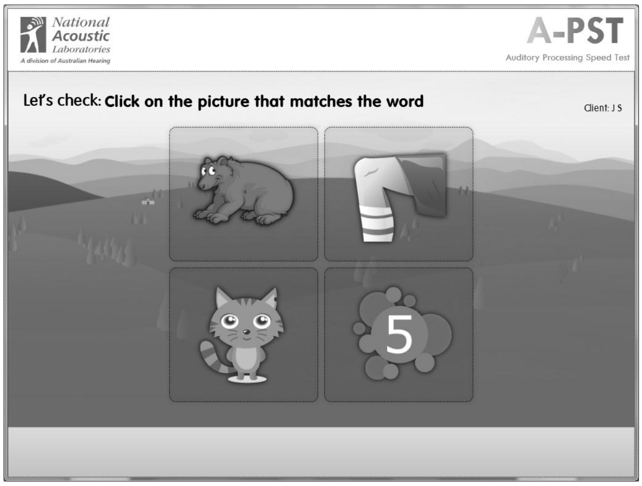

Figure 2: Screen showing Auditory Processing Speed Test (A-PST) word familiarization task.

The target words and foils were spoken by a female speaker (the first author) in a general Australian accent. General Australian is the stereotypical variety of Australian English used by the majority of Australians and it dominates the accents found in contemporary Australian-made films and television programs. Recording took place in a chamber, anechoic above 50 Hz. The stimuli were recorded on a personal computer using Adobe Audition version 3.0, an M-AUDIO mobile pre USB audio interface and a Sennheiser ME64 cardioid microphone with a foam sock. The recordings were edited using Adobe Audition 3.0. Each word was saved as an individual speech file. These files were cut 5 ms before the start of the word and 5 ms after the end of the word. Each word file was then level normalized to have a root mean square (RMS) level of -22.0 dB re: digital full scale. The average length of the targets and foils was 718 ms.

Presentation level of the A-PST is set from the calibration screen using a reference signal (modulated white noise) that is adjusted by the

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child using a slider bar. The child is instructed to move the slider bar until he or she can barely hear the whooshing sound in the headphones. The reference signal is level normalized so that its RMS level is 40 dB less than the average RMS level of the speech stimuli (target and foil words). Thus, when presented, the sensation level of the speech stimuli is at least 40 dB SL.

The targets and foils are randomly generated in real time using a random number generator. Thus the exact presentation order of the targets and foils differ between participants. Rules for random generation were implemented to result in maximum uncertainty. Thus identical targets may be generated in succession (e.g. hen, one, plate, one). However, to ensure that limitations in motor reaction time at low ISIs do not impact results targets cannot be generated in immediate succession (e.g. hen, one, three, plate).

The stimuli are initially presented at an ISI of 2000 milliseconds (ms). The ISI is adjusted adaptively. That is, if the child correctly identifies two consecutive targets the ISI is decreased (made harder). If a target is missed or if the child clicks the mouse when a foil is presented the ISI is increased (made easier). The initial step size is 400 ms, which is held constant for the first ten targets. From the eleventh target on, after each reversal in performance, the new step size equals the maximum of 12.5 ms or the previous step size multiplied by a constant k. The value of k is 0.5. In other words, the adjustment in step size is half of the previous step size in ms, with the minimum adjustment being 12.5 ms. The maximum ISI is 2000 ms.

Visual feedback is provided throughout practice and testing. A green tick appears in the response box when the child correctly identifies a target word (true positive). A red cross appears if the child selects a foil (false positive), or misses a target word. The first ten targets are always presented as practice and not included in the calculation of processing speed. To ensure that a child has the best chance of reaching threshold before scoring commences, the practice period continues until there has been one reversal in performance following the presentation of the tenth target. Testing ceases when 50 scored targets (i.e. excluding practice) have been presented.

Results are displayed at the end of test by selecting the View A-PST Results button. Results can also be exported to an Excel spread sheet from the main menu screen. The following information is provided:

- Average processing speed (APS) calculated in words per minute (wpm) using the formula: 60/(average ISI + average duration of stimulus).
- Total number of targets correctly identified- or true positives (TP) - from a possible total of 50.
- Total number of foils, or false positives (FP), selected.
- Reaction time (RT) in ms, measured as the time from the commencement of a target stimulus to the time when the child clicks on the response box, averaged across all targets correctly identified.

Results

Analyses were performed with Statistica 10.1. Table 2 documents the mean scores and SDs - averaged across age groups - for each of the four A-PST performance measures (average processing speed (APS) in wpm; true positives (TP); false positives (FP) and reaction time (RT) in ms.). Two additional measures were calculated to enable further evaluation of the data:

- Impulsivity, measured as false positives divided by true positives.
- Stimulus onset asynchrony (SOA) in ms. SOA is measured as from the start of a stimulus to the start of the next stimulus and was calculated as 1000*60/APS in wpm.

To enable results from participants in Years 1 to 6 to be combined in various analyses, scores for students in each school grade (1 to 6) were standardized to a mean of zero and unity standard deviation and reported as z-scores. APS in wpm (z score) was approximately normally distributed for the 174 participants in this study based on the Kolmogorov–Smirnov goodness of fit test ($D = 0.06$, Lilliefors-$p = 0.2$), as shown in the normal probability plot provided as Figure 3.

	Mean	SD	Minimum	Maximum
APS (wpm)	47	14	22	79
APS (wpm) Z score	0.0	1.0	-2.1	2.3
RT (ms)	827	187	526	1590
SOA (ms)	1391	468	759	2696
True Positives	37	5	25	49
False Positives	9	5	1	25
Impulsivity	0.27	0.17	0.02	0.93
APS = average processing speed; RT = reaction time; SOA = stimulus offset asynchrony; wpm = words per minute; ms = milliseconds				

Table 2: Results on the various A-PST measures averaged across age groups (n = 174). Results are expressed as mean scores, SDs and minimum and maximum scores (range). Impulsivity is measured as false positives/true positives.

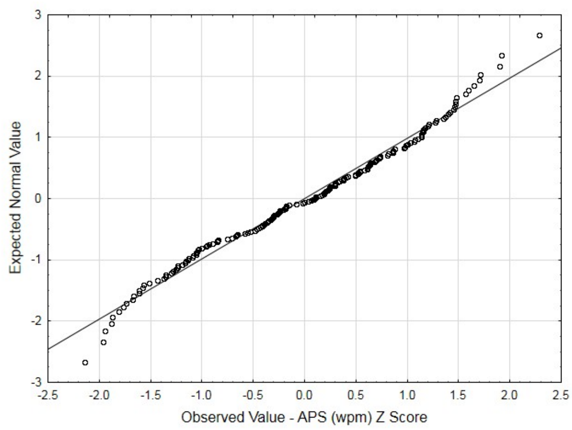

Figure 3: Normal probability plot of Auditory Processing Speed (PST) in wpm (z score).

Analysis of variance (ANOVA) was performed to determine the effect of school grade on performance on the A-PST. The dependent variable was APS in wpm and the categorical variable was school grade. A dot plot of APS in wpm against school grade is provided as Figure 4. There was a significant main effect of grade, $F(5, 168) = 12.16$, $p < 0.0000001$, $\eta p2 = 0.27$. Post Hoc comparisons (Tukey HSD test) revealed that the auditory processing speed of children in grades 1 and 2 (mean 39 wpm and 40 wmp respectively) was significantly slower than the processing speed of children in grades 5 and 6 (mean 56 wpm and 59 wpm respectively). The processing speed of children in grades 3 and 4 (both mean 47 wpm) was significantly slower than for those in grade 6.

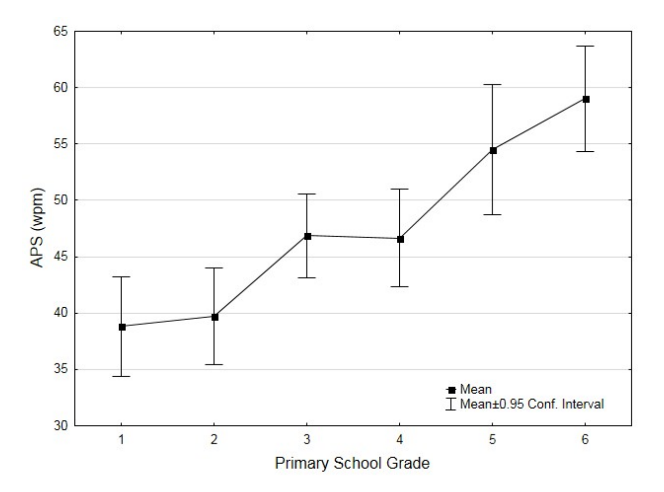

Figure 4: Average processing speed (APS) in wpm plotted against primary school grade (1 to 6) (n=174).

Effect of Age and Gender on A-PST Performance

Regression analysis with APS in wpm as the dependent variable and age as the predictor variable showed that age was a significant predictor of performance on the A-PST ($t(172) = 7.03$, $p < 0.000001$, $r = 0.47$, $b = 4.035$, $SE = 0.574$). Thus, each one year increase in age resulted in an increase in processing speed of 4 wpm. In order to control for the effect of age, APS in wpm was calculated for each participant as age-corrected population standard deviation units from the mean (z scores). This allowed for calculation of cut-off scores at which performance was considered outside normal limits (outside 1.96 SD from the mean). These cut-off scores are shown on the scatterplot of age verses APS in wpm provided as Figure 5.

In respect to the effect of gender, the z score for APS in wpm for males (0.00) was only 0.01 population SDs higher than for females (-0.01). As expected, ANOVA revealed no significant difference between the groups ($F(1, 172) = 0.023$, $p = 0.88$).

Reaction time and performance on the A-PST

In order to investigate whether reaction time limited performance on the A-PST, a regression analysis was conducted with stimulus offset asynchrony (SOA) in ms as the dependent variable and reaction time (RT) as the predictor variable. Whereas RT was a significant predictor of SOA ($t(172) = 25.31$, $p < 0.0000001$, $b = 2.23$, $SE = 0.088$), as can be seen from the scatterplot provided as Figure 6, across the entire range of performance, mean reaction time is considerably less than the mean interval from stimulus onset to the following stimulus onset.

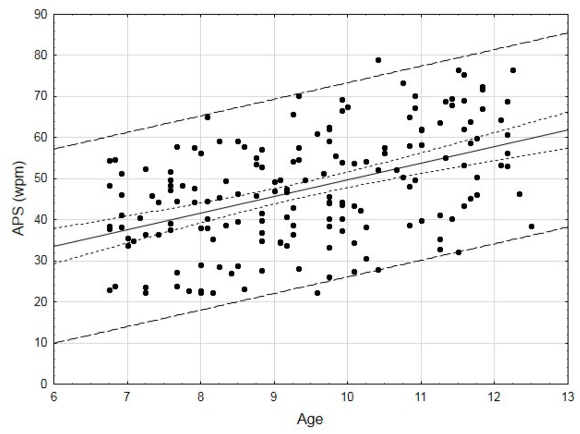

Figure 5: Scatterplot showing relationship between average processing speed in wpm and age. Dotted lines represent the 95 percent confidence intervals from the mean. Long dashed lines represent the 2 SD upper and lower limits of normal performance on the A-PST.

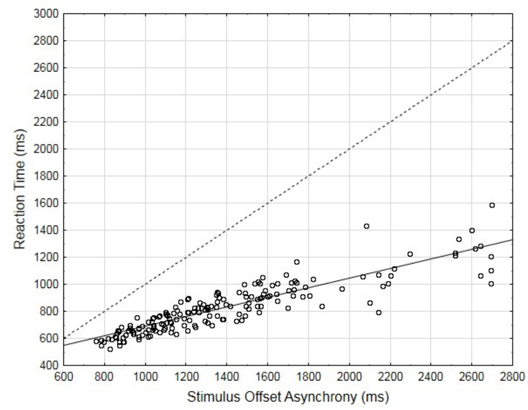

Figure 6: Scatterplot showing relationship between reaction time in ms on the A-PST and stimulus offset asynchrony (solid line). Dashed line represents parity.

Impulsivity and performance on the A-PST

A rating of impulsivity was calculated for each participant as the number of false positives divided by number of correct targets. There was no significant correlation between impulsivity and age ($r = -0.05$, $p = 0.489$). A regression analysis was conducted with impulsivity as the predictor variable and APS in wpm (z score) as the dependent variable. Impulsivity was a significant predictor of processing speed ($t(172) = 7.015$, $p < 0.0000001$, $Beta = 0.472$, $SE = 0.067$). Thus, each 1 SD increase in impulsivity rating resulted in a 0.47 SD increase in APS in wpm. A scatterplot showing the relationship of impulsivity and processing speed as Figure 7.

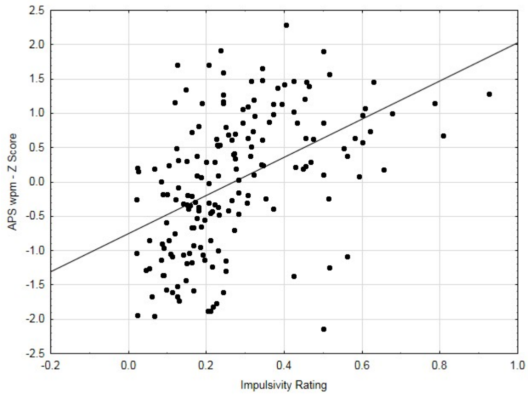

Figure 7: Scatterplot showing relationship between impulsivity rating and APS in wpm (z score).

Discussion

The brain's speed of processing is an important factor in determining how quickly a person can think, take in sensory information, or conduct other cognitive processes such as remembering or comprehending language. Whereas the majority of information presented in the classroom is auditory in nature, tests of processing speed typically utilize visually-presented materials. The purpose of this pilot study was to develop and evaluate an automated and adaptive test of processing speed – the A-PST - which utilized auditory stimuli. Further, the study aimed to investigate if processing speed for auditory stimuli improved with age; the relationship between processing speed and reaction time, and the effect of impulsivity on test performance.

Performance on the A-PST was normally distributed across the 174 primary school children who took part in this study. Average processing speed ranged from 39 wpm for children in grade 1 to 59 words per minute for children in grade 6. The processing speed of older children was significantly faster that for those in earlier grades. Regression analysis showed that for each one year increase in age, processing speed for auditory stimuli increased by 4 words per minute. Reaction time in ms on the A-PST - measured as the time from the commencement of a target word to when the child uses the computer mouse to click on the response box – was approximately half the value of the stimulus offset asynchrony (measurement in ms from the start of one stimulus to the start of the next). This shows that a child's reaction time did not limit their ability to respond to the A-PST stimuli.

A child's impulsiveness on the A-PST (measured as false positives divided by true positives) was shown to impact processing speed, with each 1 SD increase in impulsivity resulting in a 0.47 SD increase in average processing speed (APS) in wpm. The positive correlation between impulsivity and processing speed suggests a fault in the test design in that increased impulsivity is "rewarded" with a higher measured processing speed. An increase in the effect of false positives relative to the effects of true positives and/or false negatives in controlling the inter-stimulus interval (ISI) adaptation rules could potentially remove this effect.

Conclusions and Future Research

Based on the above results it can be concluded that the A-PST has potential as a test of a child's ability to process auditory stimuli. How this ability relates to visual processing speed and academic performance will be the emphasis of future research. However, the current study has exposed some issues with the test design that should be addressed prior to commencement of future research. In addition to the impact of impulsivity, some of the younger children expected to see pictures on the screen during the A-PST test session like they had during the familiarization task. In hindsight, it is not vital for the children to be familiarized with the foils as it is not a requirement of the A-PST to respond to these stimuli. For future studies it is suggested that the familiarization and instruction videos be replaced with a short instruction video advising the child to click on the square when he or she hears a number and to ignore any other words. Inclusion of a separate practice task at a fixed ISI whereby the child must identify the five target numbers and respond appropriately before proceeding to the test session would be sufficient to ensure understanding of the test rules.

Further, many of the grade 1 and 2 children had difficulty comprehending the calibration task and some of the youngest children had fine motor skills issues, experiencing difficulty manipulating the computer mouse to keep the curser inside the response box. Redevelopment of the calibration procedure, and development of the Windows program as an application that can be used on a tablet with a touch screen, would overcome these difficulties. Finally, to potentially shorten the length of the test, a stopping rule could be included whereby testing ceases when the standard error of measurement (SEM) falls below a pre-determined level. Inclusion of the SEM in the A-PST report will also provide a measure of intra-subject variability that could be used to monitor attention.

Future studies will then involve collection of new normative and test/retest reliability data as well as studies into the relationship of auditory and visual processing speed and the impact processing speed for auditory stimuli on academic achievement.

Acknowledgements

We would also like to thank John Seymour for his assistance in the recording of the speech stimuli for the A-PST and Mark Seeto for his assistance with statistics.

Appendix A

A-PST Video of Familiarization Task Instructions: Before you take a test we need to make sure that you know the names of some objects and numbers that you'll hear during the test. Let's begin. Here you can see a dog, the number three, a nose and a park. When you hear the name of an object or number, click the matching object or number on the screen. (A dialogue box appears instructing the user to start the familiarization task by clicking on the Start A-PST Now button.)

A-PST Video of Test Instructions: Welcome to the A-PST. It stands for Auditory Processing Speed Test. You'll hear a lady say some words. These words are either objects, like dog or cup, or the number one, two, three, four and five. When you hear a number click on the big square in the middle of the screen. Don't click on the square if you hear the name of an object. Only click if you hear a number. When you hear a number click on the square as soon as you can. As you do the test you will see the sun move across the screen. When the test is finished you'll see this screen*. Good luck. * A dialogue box which reads "Congratulations. You have just finished the A-PST Test! Now select an action".

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