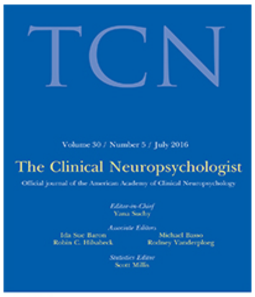

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Southwestern Assessment of Processing Speed (SWAPS): A new brief test with demographically-corrected norms in an ethnically and educationally diverse population

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Southwestern Assessment of Processing Speed (SWAPS): A new brief test with demographically-corrected norms in an ethnically and educationally diverse population

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ABSTRACT

Objective. Neuropsychological measures of processing speed have long been used as sensitive indices of cognitive functioning. Most of these commonly used tests are proprietary, and there is a need for brief, freely available tools that can be used in diverse clinical and research settings. The Southwestern Assessment of Processing Speed (SWAPS) is a 60-second digit-symbol transcription task developed as a brief alternative to commercially available coding tests. Demographically-corrected normative data are presented along with reliability and sensitivity/specificity values in older adults with and without cognitive impairment.
Method. SWAPS data from 915 healthy aging individuals (NC) and 858 subjects with clinical diagnoses of mild cognitive impairment (MCI; n = 430) and Alzheimer's disease clinical syndrome (ADCS; n = 428) were obtained from the Texas Alzheimer's Research and Care Consortium (TARCC). TARCC participants represent ethnically and educationally diverse community-dwelling individuals age 50+.
Results. SWAPS scores showed the expected associations with age, sex, and education, and the interaction between age and education were significant predictors of SWAPS scores. Test-retest reliability in NC was good, and the SWAPS distinguished impaired and non-impaired groups with adequate to excellent sensitivity and specificity for the primary analyses, with optimal cut-off points provided. Raw score- to uncorrected normalized T-scores and demographically-corrected SWAPS T-scores using regression-based

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norms are presented along with scoring programs for the calculation of each.
Conclusions. The SWAPS is a brief, free, easily administered test with demographically-corrected regression-based norms and promising utility for detection of cognitive impairment and efficient assessment of processing speed.

Introduction

The brain's ability to rapidly process information is a key feature of cognitive efficiency, and reduced processing speed has been shown to be associated with lower cognitive performance on a variety of tasks, including measures of learning, memory, and executive functioning (Fellows et al., 2014; Salthouse, 2000). As a result, tests of processing speed have long been a cornerstone of cognitive and intellectual assessment measures over the past 70+ years. Factor analyses of the various versions of the Wechsler Scales, for example, have consistently demonstrated a processing speed factor (Holdnack et al., 2011). Additional studies of processing speed have demonstrated an inverse relationship with aging (Machulda et al., 2013; Salthouse, 2000) and have shown sensitivity to acquired cerebral dysfunction across a wide range of cognitive disorders, including traumatic brain injury (Mathias & Wheaton, 2007), multiple sclerosis (Chiaravalloti & DeLuca, 2008), Parkinson's disease (Zgaljardic et al., 2003), and Alzheimer's disease/dementia (Finkel et al., 2007; Finkel & Pedersen, 2004; Gurnani & Gavett, 2017). Such tasks often involve multiple cognitive abilities including visual attention and scanning, working memory, rapid decision making, and psychomotor speed, which no doubt contribute to the tests' sensitivity and combine to form the construct of "processing speed."

There are currently a number of commercially available measures of processing speed that are in popular clinical use, including the Coding/Digit Symbol subtest of the Wechsler Intelligence Scales (e.g., WAIS-IV; Wechsler, 2008) and the Symbol Digit Modalities Test (SDMT; Smith, 1982), in addition to similar number-symbol coding tasks that are included in brief test batteries such as the Repeatable Battery for the Assessment of Neuropsychological Status (RBANS; Randolph et al., 1998) and the Battery for the Assessment of Cognition in Schizophrenia (BACS; Keefe et al., 2004). These tasks typically show strong correlations (*r*s = .8 to .9) with one another in healthy and clinical samples (e.g., see McKay et al., 2007; Morgan & Wheelock, 1992).

WAIS-IV Coding, and its predecessors from the earlier versions of the Wechsler Adult Intelligence Scale (i.e., WAIS-IV, WAIS-III, WAIS-R, WAIS, Wechsler-Bellevue), is a very popular coding/substitution task that requires examinees to copy symbols paired with numbers in a key at the top of the page into boxes below that only show the associated number. The raw score (maximum = 135) is based on the correct number of substitutions completed in 120 seconds and is corrected for age to provide a scaled score. Among all the Wechsler Intelligence Scale subtests, Coding tends to be the most sensitive to cognitive impairment in general due to its multifactorial nature and dependence upon perceptual comparison speed as a key component (Jaeger, 2018;

Salthouse, 1992). While Coding is often administered as part of the WAIS-IV and other test batteries, it is also used in clinical and research settings as a singular measure of processing speed.

Similarly, the SDMT is another popular symbol substitution task that requires examinees to substitute a number (1 through 9, orally or written) for various geometric shapes, displayed in a key at the top of the page. The score is based on the correct number of substitutions (maximum = 110) completed in 90 seconds. Developed as a screening measure to detect cerebral dysfunction in children and adults (Smith, 1982), it has been used in a wide array of clinical populations to assess processing speed. The SDMT is included as part of a number of standard neuropsychological test batteries (e.g. NHL and NFL concussion test batteries, and the Minimal Assessment of Cognitive Function in Multiple Sclerosis). A review of the use of the SDMT as a cognitive outcome measure supports its application as a valid and reliable index of processing speed that is also useful in evaluating cognitive change over time in various conditions such as multiple sclerosis (e.g. Benedict et al., 2017).

With recent advances in technology, many computerized processing speed tasks have been developed, with some adopting similar formats to the familiar symbol-coding paradigm. As one example, a self-administered iPad-based symbol coding task (the Processing Speed Test, PST) was designed and introduced as a cognitive screening measure for use in patients with multiple sclerosis (Rao et al., 2017). Similar to other number-symbol coding tasks, the key is shown at the top of the screen and consists of symbols paired with numbers, though the pairing is randomly generated for each administration to minimize learning effects. Subjects are instructed to use a keyboard on the bottom of the screen to select the number that goes with each symbol as quickly as possible for 120 seconds. PST scoring is automatic and reflects the total number of correct symbol pairs identified. Preliminary findings using the PST showed a high correlation ($r = .78$) with the SDMT and good ability to distinguish patients with multiple sclerosis from healthy controls (Rao et al., 2017).

Demographic effects on processing speed measures have been well-documented and are an important consideration in normative test development. Specifically, age, sex, and education have been found to relate to performance on many neuropsychological tests, including processing speed measures, with a noticeable decline with advancing age (often beginning in the 40 s or 50 s), a tendency for women to outperform men, and those with higher education generally obtaining higher scores on such tests (Heaton et al., 1996, 2003; Rivera Mindt et al., 2021; Salthouse, 2000). Overall, age has most consistently been shown to have an effect on tests of processing speed, while sex and education have also shown to be significant predictors of performance. With regard to sociodemographic and related effects, processing speed measures are sometimes considered to be less influenced by sociocultural factors; however, the available research on the effects of race/ethnicity/culture and related factors is limited and has mixed findings. For example, O'Bryant et al. (2007) examined SDMT performance in diverse samples of college students (Caucasian, Black, Asian, and Hispanic) and patients with hepatitis C (Caucasian and Hispanic) and found no significant race/ethnic group differences on SDMT performances. In contrast, Rivera Mindt et al. (2021) found that rates of impairment on WAIS-III Coding scores were significantly overestimated when applying widely used English-speaking non-Hispanic

White adult norms (adjusted for age, gender, and level of education) to a sample of healthy native Spanish-speaking participants from the US-Mexico border region. Similarly, the large diverse international normative aging study of the SDMT by Ryan and colleagues (Ryan et al., 2020) found significant effects of age, education, and sex, with additional ethnoracial effects observed. Along these lines, in terms of normative studies of neuropsychological tests, it has been noted that traditional compartmental age-band norms using means and standard deviations have the limitation of small sample sizes when multiple demographic variables are factored in. More modern regression-based normative approaches allow for capturing multiple demographic factors in a continuous fashion, resulting in greater precision for estimating where an individual's scores fall relative to their peers (Fellows & Schmitter-Edgecombe, 2019; Stricker et al., 2021).

Because symbol-digit substitution tasks are brief (usually 90-120 seconds), easily administered and scored, and sensitive to cognitive dysfunction, they are often included as part of both screening and more comprehensive neuropsychological evaluations. Most of the current symbol/coding tests are widely available and require only a pencil/paper and a standard record form available from the respective test publishers. While these tests are relatively low cost (i.e., $2.50 to $3.40/form), each copyrighted form does require purchase in most cases (exceptions may include applications in research). Thus, a limitation of the most popular current commercially available measures is the cost, particularly when large numbers of subjects/patients are being evaluated longitudinally. The development of a new tool that assesses processing speed also adds to the armamentarium of available measures which may enhance incremental validity when examining for cognitive deficits in a brief manner and help avoid practice effects when the same tests are repeatedly administered in clinical and research settings. Having such a measure that is based upon modern norming procedures in a diverse population may also have benefits in generalizability.

The purpose of the current investigation was to 1) establish preliminary regression-based normative data for a brief (60 seconds), new, and cost-efficient number-symbol substitution test, the Southwestern Assessment of Processing Speed (SWAPS), in racially/ethnically and educationally diverse subjects age 50–90, 2) to examine the effects of age, education, and sex on SWAPS performance, 3) explore test-retest reliability, and 4) examine the ability of SWAPS to distinguish cognitively impaired and non-impaired groups and establish initial cutoff scores for impairment.

Method

Participants

Male and female community-dwelling volunteers age 50 and above were obtained from the Texas Alzheimer's Research and Care Consortium (TARCC) database. TARCC is a state-funded collaboration between Texas medical institutions with specialized dementia clinics dedicated to improving the diagnosis, treatment, and care of individuals with Alzheimer's disease (see txalz.org). TARCC was established as a longitudinal database with standard diagnostic procedures and annual evaluations (Waring et al., 2008). At the time of data collection for the SWAPS (2014–2015 calendar years), TARCC clinical sites included five institutions: The University of Texas Southwestern Medical Center, Baylor College of Medicine, Texas Tech University Health Sciences Center, The University of Texas Health Science Center at San Antonio, and The University of North Texas Health Science Center. TARCC clinical diagnoses were made following consensus review of standard TARCC examinations (Waring et al., 2008), including medical history, neuropsychological data, clinical interview, neurologic examination, and assessment using the Clinical Dementia Rating (CDR; Morris, 1993) by a multidisciplinary group of clinicians at each site in accordance with accepted clinical diagnostic procedures (McKhann et al. 2011). For this study, three groups of subjects were selected from the TARCC database who were administered the SWAPS as part of the standard neuropsychological battery. This included cognitively normal controls (NC; n = 915), subjects with mild cognitive impairment (MCI; n = 430), and those with a clinical diagnosis of Alzheimer's disease (ADCS; n = 428) at initial testing. The SWAPS was administered at two time points, approximately one year apart, to a subgroup of 539 NC volunteers as part of the TARCC neuropsychological battery at participating institutions. The SWAPS was not used in the diagnostic process, and all SWAPS scores from the available subject groups were included for analysis. Demographic characteristics of the sample are provided in Table 1.

Materials

The SWAPS was developed as a brief number-symbol substitution test. It is presented on a standard 8.5″x11″ sheet of paper and consists of seven common shapes, each paired with a scrambled, non-sequential number between one and seven in the key at the top of the page. All the shapes are easily recognizable, distinct from each other, and derived from symbols available in *Microsoft Word*. The page is organized with a nine row by nine column configuration of items below the key. Each item consists of a shape large enough for a number to be easily written inside. This format (writing numbers within symbols) was chosen in order to facilitate ease of response (familiarity with numbers) and scoring. The first six items in the first row include three demonstration items completed by the examiner, followed by three practice items completed by the subject. Once these six items are completed and the subject has demonstrated adequate understanding of the task, they are instructed to continue filling in the appropriately matched numbers that go with each symbol, moving from left to right, then row by row down the page, *as quickly as possible*, without skipping any, for 60 seconds. The maximum possible raw score is 75, with the total score reflecting the total number of correct responses. SWAPS test forms, instructions, and scoring tool are hosted in REDCap (Harris et al., 2009, 2019) and are available for download at https://redcap.link/SWAPS.

Procedure

All subjects provided written and verbal informed consent prior to participation in TARCC, and the research protocol was approved by the institutional review boards at

Table 1. SWAPS scores and demographic characteristics by group (n = 1773).

Characteristic	NC (n = 915)		MCI (n = 430)		ADCS (n = 428)	
	n	%	n	%	n	%
SWAPS total raw score (M, SD)	M = 29.59	SD = 7.91	M = 24.44	SD = 7.61	M = 14.49	SD = 8.43
Sex (Female)	635	69.4%	248	57.7%	219	51.2%
Age, years (M, SD)	M = 68.21	SD = 9.19	M = 73.03	SD = 7.56	M = 76.31	SD = 8.63
50-59	171	18.6%	19	4.4%	18	4.3%
60-69	356	38.9%	108	25.1%	77	18.0%
70-79	264	28.9%	217	50.5%	164	38.3%
80-89	114	12.5%	82	19.1%	153	35.7%
90-95	10	1.1%	4	0.9%	16	3.7%
Education, years (M, SD)	M = 13.01	SD = 4.55	M = 12.38	SD = 4.36	M = 13.8	SD = 4.11
0-7	138	15.0%	65	15.1%	40	9.3%
8-12	259	28.3%	154	35.8%	113	26.4%
13-15	181	19.8%	95	22.1%	80	18.7%
16	149	16.3%	55	12.8%	107	25.0%
17-20	187	20.5%	61	14.2%	88	20.6%
Unknown	1	0.1%	---	---	---	---
Race/Ethnicity						
Hispanic Any Race	445	48.7%	244	56.8%	99	23.1%
White	429	46.9%	160	37.2%	311	72.7%
Black/African American	36	3.9%	26	6.0%	16	3.7%
Asian	4	0.4%	2	0.5%	---	---
American Indian/Alaska Native	1	0.1%	---	---	---	---

Note: SWAPS = Southwestern Assessment of Processing Speed; NC = Healthy aging individuals; MCI = Mild cognitive impairment; ADCS = Alzheimer's disease clinical syndrome.

each participating medical center. TARCC participants underwent a standard battery of neuropsychological tests administered by trained personnel that included the SWAPS at initial visit and approximately one year later for a subset of the healthy controls.

Statistical analysis

Regression-based norms were developed through multiple regression analyses (MRA) following procedures described in other studies (Parmenter et al., 2010; Smerbeck et al., 2011). First, SWAPS raw scores from the 915 NC participants were normalized using Blom's formula (Blom, 1958). Second, the resulting z-scores were transformed into uncorrected normalized SWAPS T-scores (M = 50, SD = 10). Third, the uncorrected normalized SWAPS T-scores were used as a dependent variable in the MRA with demographic predictors (age, sex, education). Age (years) was centered by subtracting NC mean age (M_{age} = 68.21). Both age-centered (Agec) and age-centered squared ($Agec^2$) were included in the MRA to reduce potential multicollinearity (Burggraaff et al., 2017; Fellows & Schmitter-Edgecombe, 2019). Predicted SWAPS T-scores were computed from Agec, $Agec^2$, sex (0 = female, 1 male), education (years) and all two-way interactions. Only the interaction of Agec and Education was significant and all other interactions were excluded from the final MRA. In addition, $Agec^2$ was not significant and was excluded from the final model. The final model is: SWAPS $T\text{-score}_{predicted}$ = intercept + B_{agec} (agec) + B_{sex} (sex) + $B_{education}$ (education) + $B_{agecXeducation}$ (agec x education). Demographically-corrected SWAPS z-scores were calculated as (uncorrected normalized SWAPS T-score – predicted SWAPS T-score)/Root Mean Square Error (RMSE). Finally, these z-scores were transformed into demographically-corrected SWAPS T-scores with M = 50, SD = 10.

SWAPS raw score test-retest reliability for controls was calculated using the intra-class correlation coefficient (ICC) and the one-way random-effect model with a 95% confidence interval (CI). The reliability estimate was interpreted as follows: <0.70 as unacceptable clinical significance, 0.70 – 0.79 as fair, 0.80 – 0.89 as good, and >0.90 as excellent (Cicchetti, 1994). Receiver operating characteristics (ROC) analyses were conducted to evaluate the diagnostic performance of SWAPS uncorrected normalized T-scores across NC, MCI, and ADCS groups. Sensitivity and specificity were calculated using the cut scores for the groups. IBM SPSS V26 was used to perform all statistical analyses and significance was set at p < .05. Assumptions for all statistical tests (normality, multicollinearity, linearity, homoscedasticity, etc.) were reviewed and none were violated.

Results

Demographic characteristics & normative data

The sample was diverse in terms of race/ethnicity and education as detailed in Table 1. Almost half of the normative sample self-identified as Hispanic or Latino, regardless of race (48.7%; n = 445), 46.9% (n = 429) as White/Caucasian, 3.9% (n = 36) as Black/African American, and 0.5% (n = 5) identified as "other". The NC mean level of education was 13.01 years, with a range of 0 to 20 years (max possible = 20), and 43.3% (n = 397) had ≤ 12 years of education. As seen in Table 1, SWAPS raw scores significantly differed across our clinical groups [F(2,1770) = 523.86, p < .001], with post-hoc comparisons using the Bonferroni test indicating that the NC sample had the highest scores (M = 29.59; SD = 7.91), followed by MCI (M = 24.44; SD = 7.61) and then by ADCS (M = 14.49; SD = 8.43). SWAPS data by overlapping age band groups among the NCs are presented in Table 2 to allow for easy age-referenced comparisons without demographic corrections. Clear age effects are seen across the NC sample (SWAPS raw score r with age = .207, p < .001), with older subjects obtaining lower scores than their younger counterparts, and similar SDs across groups. The overall correlation between SWAPS raw score and age across the entire sample was also significant (r = −.351, p < .001).

Demographic characteristic effects on SWAPS performance

MRA results are presented in Table 3 and graphically in Figure 1. The model predicting normative SWAPS scores accounted for almost 38% of the variance, R^2 = .378, F(4, 909) = 138.346, *p* < .001. Sex, education, and Agec*education were significantly

Table 2. SWAPS data by overlapping healthy control age bands.

Midpoint Age (years)	Age Range (years)	SWAPS Raw Score		
		n	M	SD
56	51 – 61	56	36.0	6.1
59	54 – 64	99	36.1	6.4
62	57 – 67	132	35.6	5.8
65	60 – 70	170	34.8	5.8
68	63 – 73	182	33.6	6.4
71	66 – 76	211	31.7	6.0
74	69 – 79	194	30.5	6.4
77	72 – 82	176	29.1	6.1
80	75 – 85	150	28.5	6.1
83	78 – 88	115	27.6	5.8
86	81 – 91	83	27.2	5.3
90	84 – 95	56	27.2	5.0

Note: SWAPS = Southwestern Assessment of Processing Speed.

Table 3. Regression coefficients for SWAPS scores in the normative sample (n = 915).

Variables	B	SE B	β	t	p-value
SWAPS					
(Constant)	34.066	0.843		40.411	< .001
Agec	−0.086	0.093	−0.079	−0.920	0.358
Sex	−1.561	0.581	−0.072	−2.686	0.007
Education	1.284	0.061	0.585	21.136	< .001
Agec*Education	−0.024	0.007	−0.300	−3.539	< .001
RMSE	7.881				
R^2	0.378				< .001

Note: SWAPS = Southwestern Assessment of Processing Speed; RMSE = Root mean square error; Agec = age centered.

associated with SWAPS performance, with females and those with more years of formal education obtaining higher SWAPS scores. Agec was not a significant predictor in the model for SWAPS but was retained because of its significant interaction effect with education.

Table 4 depicts the overall simple conversion from SWAPS raw-to-uncorrected normalized T-scores to provide an at-a-glance T-score conversion. Semi-automated scoring programs to calculate uncorrected normalized and *demographically-corrected SWAPS T-scores* (age, education, sex, age x education) can be downloaded from the following webpage: https://recap.link/SWAPS.

Test-retest analysis

Test-retest reliability was calculated for a subset of 539 NC participants who completed the SWAPS at two time points roughly one year apart (M = 11.2 months; SD = 1.4). This sample did not differ from the total NC group in terms of age, education, sex, ethnicity, or total raw SWAPS scores. Test-retest reliability for SWAPS was high, with an ICC of 0.89 [95% confidence interval (CI), 0.866 – 0.904].

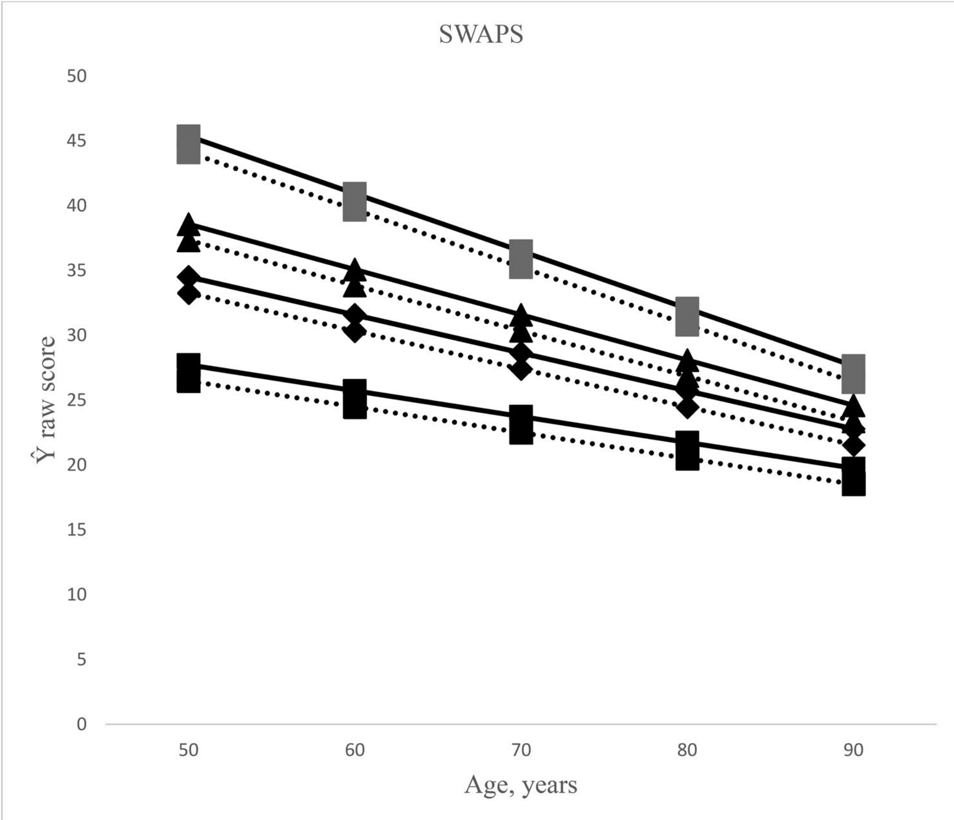

Figure 1. Regression model.

Note: The predicted T-scores for Southwestern Assessment of Processing Speed (SWAPS) were demographically adjusted using MRA and the following independent predictors: Agec/sex/education/age*education. The predicted T-scores were converted into raw scores and are presented in this figure. Graph shows the effect of age, sex (women, solid lines; men, dashed lines), and years of education (black squares, 7 years; diamonds, 12 years; triangles, 15 years; grey squares, 20 years) on Ŷ converted to raw scores.

Diagnostic cut-off points

Three ROC analyses were carried out and the predictive values were determined to evaluate SWAPS accuracy to discriminate between the clinical groups: NC vs ADCS, MCI vs ADCS, and NC vs MCI. Figure 2 displays the graphic representations of the ROC curves.

SWAPS demonstrated an excellent ability to discriminate between NC and ADCS groups, with an area under the curve (AUC) of 0.905 [95% CI, 0.889 – 0.921], and between MCI and ADCS, with an AUC of 0.807 [95% CI, 0.779 – 0.839]. As expected, SWAPS scores were less able to discriminate between NC and MCI groups, with an AUC of 0.690 [95% CI, 0.660 – 0.719]. A SWAPS uncorrected normalized T-score cut-off point of above 39 provided optimal discrimination between NC and ADCS

Table 4. Converting SWAPS raw scores to uncorrected normalized SWAPS T-scores.

SWAPS raw score	Uncorrected normalized SWAPS T-score
0 – 3	20
4	22
5	23
6	25
7	26
8 – 9	27
10 – 11	28
12	29
13	30
14	32
15	33
16	34
17 – 18	35
19	36
20	37
21	38
22	40
23	41
24	42
25	44
26	45
27	46
28	48
29	49
30	50
31	52
32	53
33	55
34	56
35	57
36	58
37	59
38	61
39	63
40	64
41	65
42	66
43	68
44 – 45	69
46	70
47	71
48	73
49	75
50 – 51	76
52 – 53	77
54 – 75	80

Note: SWAPS = Southwestern Assessment of Processing Speed.

[sensitivity (86%), specificity (78%), classification accuracy (84%)], and a score above 37.5 provided good discrimination between MCI and ADCS [sensitivity (75%), specificity (73%), classification accuracy (74%)]. Additionally, a SWAPS cut-off point of above 45.5 provided optimal discrimination between NC and MCI (sensitivity = 68%, specificity = 60%), though classification accuracy was lower than that seen in the other groups (65%).

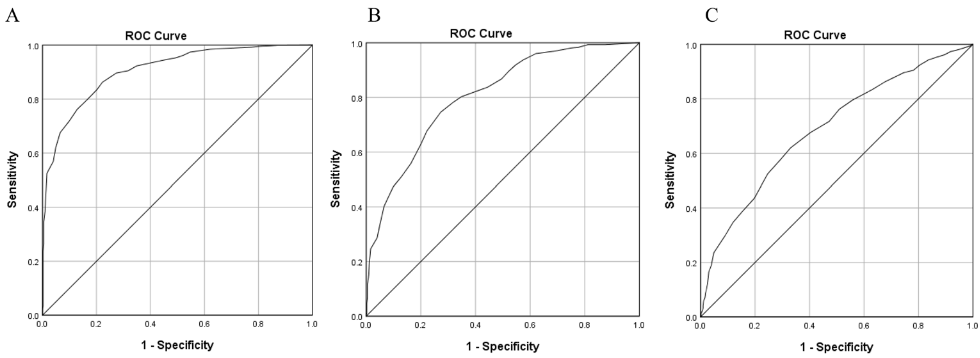

Figure 2. Receiver operating characteristic (ROC) curve analysis of Southwestern Assessment of Processing Speed (SWAPS) using uncorrected normalized T-scores.
Note: A: Healthy aging individuals (NC) vs Alzheimer's disease clinical syndrome (ADCS), area under the curve (AUC) = 0.905 [95% CI, 0.889 – 0.921]; B: Mild cognitive impairment (MCI) vs ADCS, AUC = 0.807 [95% CI, 0.779 – 0.839]; C: NC vs MCI, AUC of 0.690 [95% CI, 0.660 – 0.719].

Discussion

Mental processing speed has long been recognized as a sensitive indicator of cerebral dysfunction across a variety of cognitive disorders (de Jager et al., 2003). Accordingly, a number of brief tests of processing speed have been developed, and the symbol-digit or digit-symbol coding task style has proven popular and clinically efficient. The SWAPS was created as an alternative to similar tests in common use that require a fee, ordering forms, and take slightly longer to administer or require computer equipment.

In the present study, regression-based demographically-corrected normative data for the SWAPS were established in a diverse older cognitively normal sample. This approach to normative reference values provides for a number of advantages over traditional age-band norms and conventional look-up tables, including a continuous (as opposed to discrete) representation of data which considers in multiple demographic factors to enhance precision (e.g. see Fellows & Schmitter-Edgecombe, 2019). SWAPS scores were influenced by age and education, with younger and more highly educated individuals obtaining higher scores. These findings are consistent with prior research using similar processing speed tests (e.g., Heaton et al., 1996, 2003; Siedlecki et al., 2019). In particular, SWAPS raw scores showed a small but significant inverse correlation with age (–.207 in controls), with older subjects obtaining lower scores, as expected. This is generally consistent with the literature depicting the well-known negative effects of age on processing speed (Deary et al., 2010; Salthouse, 2000) but is a smaller effect than found with other symbol coding tests which have shown that age often accounts for up to 50% of variance in scores (e.g., WAIS-3 Coding – age r = –.69, Joy et al., 2004; BACS Coding-age r = –.55, Keefe et al., 2004). There was a significant interaction between age and education in predicting SWAPS T-scores, such that participants with more years of education had larger age effects on the SWAPS compared to participants with fewer years of education (See Figure 1). Of note, females scored significantly but only slightly higher than males (1.21 raw scores points, 1.56 T-score points overall) on the SWAPS, even after accounting for other demographic variables in our older NC subjects. This is consistent with sex differences reported on other processing speed tasks. For example, analysis of the WAIS-III standardization sample by Irwing (2012) showed higher mean Digit Symbol scaled scores of approximately 1.3 scaled score points in females (M = 10.60) vs. males (M = 9.27). Similarly, females have shown better performance than males on the RBANS coding test, with a mean difference of 1.7 raw score points (Duff et al., 2011).

Unique to the SWAPS is its validation in a large, ethnically and educationally diverse sample. About half of the sample (43.3%) had less than 13 years of education, with a range of 0 to 20 years. Education was a significant predictor of SWAPS in our sample, which is largely in keeping with findings using similar tasks. More years of education were related to better SWAPS performance, even after controlling for age. Hoyer et al.'s (2004) meta-analysis examining the effects of age and education on WAIS-R Digit Symbol found that age accounted for a majority of the variance in a regression model, with no significant relationship between education and Digit Symbol performance. Similarly, Salthouse (1992) found that age-related declines in WAIS-R Digit Symbol performance were largely independent of education. While the source(s) of these apparent discrepancies is not entirely clear, the Hoyer et al. (2004) and Salthouse (1992) samples were more limited in diversity as well as range of education (12 – 18 years). In a large international sample of more than 19,000 older diverse older individuals, age, education, and sex were all significantly related to SDMT performance, with some additional ethnoracial differences seen (Ryan et al., 2020), in support of our findings with the SWAPS. In the current study, the multiple regression-based analyses treated age as a continuous variable rather than using dichotomous age groups, which may provide more robust and meaningful results (e.g. see Fellows & Schmitter-Edgecombe, 2019). Furthermore, it is possible that the nature of the SWAPS stimuli and procedures (i.e., writing non-sequential numbers inside of familiar symbols) contributes to the reduced correlation with age compared with some studies using other similar tasks that require subjects to copy symbols that may be less familiar to subjects of diverse backgrounds.

Despite its brevity, the SWAPS showed good test-retest reliability (ICC = 0.89) in our healthy participants (n = 539) who completed the test after an approximately one-year interval. This is in keeping with other popular processing speed measures that often examine retest reliability over shorter periods of time. For example, test-retest reliability over a 22 day period for WAIS-IV Digit-Symbol Coding was r = .83 as reported in the standardization manual (Wechsler, 2008, p. 48). Likewise, studies of the SDMT in healthy adults have shown test-retest reliability coefficients ranging from r = .70 to .80 at 1-month (Smith, 1982), and BACS Coding showed an ICC of.83 in healthy controls tested over 1-3 days (Keef et al., 2004). Thus, the test-retest reliability of the 60-second SWAPS is good, and comparable to or slightly better than other popular number-symbol coding tasks which require 90–120 seconds. Interestingly, we were unable to locate any references to support the rationale for the traditional 90–120 second time allowance on traditional symbol-coding tasks, though our findings suggest that slightly shorter processing speed tasks can maintain sensitivity/specificity if properly constructed. The comparable psychometric properties of the shorter SWAPS may also relate to the greater challenge of the non-sequential presentation of the numeric stimuli in the key which may make higher demands on working memory and/or visual scanning speed as subjects must refer to the specific number-symbol pairings in the key and cannot rely upon the numeric order.

Tests of processing speed are important objective tools commonly used in the screening and assessment of cognitive impairment. As expected, SWAPS raw scores significantly differed across our clinical groups, with the NC sample having the highest scores (M = 29.59), followed by MCI (M = 24.44) and then by the ADCS group, who obtained much lower scores (M = 14.49). Additionally, ROC analyses showed an excellent ability to discriminate between NC and ADCS (using a SWAPS uncorrected normalized T-score of 39), and between MCI and ADCS (using a SWAPS uncorrected normalized score of 37.5), with sensitivities above 75%, specificities above 73%, and classification accuracies above 74%, which are in line with other coding tasks. Not surprising given the nature of the clinical diagnosis of MCI which typically involves primary impairment of episodic memory, SWAPS scores were not able to discriminate as well between NC and MCI groups (using a SWAPS uncorrected normalized T-score of 45.5). Attention and processing speed scores often vary among individuals with MCI, and we did find that the mean of our MCI group was closer to NCs, as expected, though the mean MCI scores were in between NC and ADCS groups, reflecting the mildly impaired nature of this group overall.

Processing speed has been studied for many years and has consistently proven to be sensitive to cognitive impairment as well as to the effects of normal aging. While traditional number-symbol coding tasks are brief (i.e., 90–120 seconds) and simple to complete for most individuals, they require a variety of cognitive skills, including attention, psychomotor speed, visual scanning, and working/incidental memory. Thus, it was not surprising that performance on the 60-second SWAPS test was negatively correlated with age, but interestingly, age effects were smaller than seen with other popular number-coding tests and no longer significant after accounting for the interaction between age and education. As such, education appeared to attenuate processing speed performance across age groups in our diverse sample.

Given the historical sensitivity of processing speed tasks to cerebral integrity in a variety of clinical conditions, the present findings show promise for the clinical utility of the SWAPS as a quick and cost-effective way to assess processing speed and detect/track cognitive impairment. The SWAPS requires little time to administer and score, is free to download together with its scoring file that provides demographically corrected T-scores (see https://redcap.link/SWAPS), and requires no special equipment. Future studies will need to examine the relationship of SWAPS with other neuropsychological measures, its incremental validity, longitudinal changes across clinical conditions, and the potential effects of social advantage/disadvantage and other sociodemographic factors.

Limitations

While these initial findings using the SWAPS are promising, several limitations of the study should be considered. First, although this is one of the more ethnically and educationally diverse normative samples for a processing speed test in North America, Black, American Indian/Alaska Native, and Asians were under represented, comprising less than five percent of our sample; thus, the results may not generalize to these or other sociodemographic populations. Second, this sample included subjects 50 – 95 years of age, and as such, normative performance levels may need to be established for younger individuals. While the sample sizes of most age bands were well over 100, there were only 10 subjects over age 90. This may limit the test's utility in the oldest segment of the population, although in our sample, mean scores for the oldest age bands (80 – 89 and 90 – 95) were similar, and our regression-based normative approach helps to mitigate the effects of smaller sample sizes. Third, the standard neuropsychological test battery used by TARCC did not include similar measures of processing speed, which limited our ability to compare it with like measures; however, we will examine the relationship between the SWAPS and other standard neuropsychological tests in the future once those data are assimilated. Fourth, the TARCC neuropsychological battery did not include specific measures of effort, so it is possible that some participants put forth suboptimal effort, though given the large number of subjects and regression-based normative approach to the data, the potential influence of this on the current results is likely small. Lastly, whether equivalent alternate forms can be created by reordering the symbol-number pairs remains a question.

Conclusion

The SWAPS has several advantages over other traditional commercially available measures of processing speed, including cost, easy scoring, and availability of regression-based demographically-corrected norms derived from a relatively large, ethnically and educationally diverse sample. The SWAPS has good test-retest reliability, shows promising sensitivity to cognitive impairment, and the available easy-to-use scoring program provided herein will aid clinicians and researchers in using and interpreting results as more information becomes available regarding the psychometric properties and clinical utility of the SWAPS in additional clinical populations and settings.

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No potential conflict of interest was reported by the authors.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the corresponding author, C. Munro Cullum, PhD.

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