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Executive Dysfunction and Processing Speed Predict Nonverbal Problem Solving Deficits in a Substance Use Disorder Population

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Abstract

Individuals with chronic substance use disorders have demonstrated various types of executive dysfunction, including nonverbal planning and problem solving. Prior studies that have examined the cognitive abilities that support performance of the Tower of Hanoi, a measure of nonverbal planning and problem solving task, have predominately been investigated in healthy adult populations. The present study examined how executive functions such as concept formation and cognitive flexibility, as well as information processing speed, and memory contribute to the performance of the Tower of Hanoi within a sample of 191 individuals with a substance use disorder. Results indicated that concept formation, cognitive flexibility, and information processing speed, but not memory significantly predict performance of Tower of Hanoi. The implications of this study suggest that cognitive remediation of processing speed and executive functioning, especially within the domain of concept formation and cognitive flexibility may improve nonverbal planning and problem solving within a substance use population.

Keywords

Executive function, Processing speed, Tower of Hanoi, Substance use

Introduction

Executive function is an umbrella term that pertains to many cognitive abilities, including: planning and problem solving, cognitive flexibility, response inhibition, set shifting and fluency [1]. One aspect of executive functioning of particular interest is nonverbal planning and problem solving abilities due to its relationship with real-world functioning [2,3] and treatment response [4]. Assessments of nonverbal planning and problem solving measure the individual's ability to plan, organize and sequence steps, and the execution of the plan [5-8]. Individuals with chronic substance use disorders have demonstrated various cognitive deficits in many cognitive domains [9]. Executive dysfunction is prevalent in adults with substance use, including nonverbal problem solving deficits [10]. However, it is unclear how cognitive deficits affect nonverbal planning and problem solving in the substance use disorder population. There is an increasing body of literature that has investigated the cognitive component that support nonverbal planning and problem solving, but the majority of those studies have concentrated on neurologically and cognitively intact adults [11-14].

The Tower of Hanoi (TOH) task is a well-validated, nonverbal planning problem solving task that is brief, easily administered, and presents the examinee with a well-defined problem [8,15,16]. Performance on the Tower of Hanoi has been used successfully to demonstrate nonverbal planning and problems solving deficits across a variety of clinical populations including: substance use disorder [17], traumatic brain injury [6,18], turner's syndrome [19], intellectual disability children and adults [20,21], schizophrenia [22,23], obsessive-compulsive disorder [24], and high-functioning autism [25].

Although the Tower of Hanoi has been demonstrated to be a sensitive cognitive measure of nonverbal planning and problem solving deficits in clinical populations, the cognitive abilities that subserve the Tower of Hanoi performance have predominately been investigated with healthy adult participants in the studies [13,14,26-28]. These studies demonstrate various performance measures of the Tower of Hanoi that have been used; such as the time to complete the task, number of moves to solve the puzzles, time per move, or the number of rule violations. Therefore, there is no one standard performance measure consistently used across studies. Furthermore, the cognitive abilities that subserve the nonverbal planning and problem solving, as measured by the Tower of Hanoi, is dependent on the outcome measure used in each of the studies. Welsh and colleagues developed a point system for solving the Tower of Hanoi over multiple trials with different starting points and end goals. Performance on this measure is influenced by concept formation as well as fluid intelligence [28], and processing speed [13]. Similarly, Sorel and Pennequin [27] reported processing speed predicts a Tower of Hanoi composite measure based on time to complete, number moves and number of rule violations. Similar to Welsh's studies, Zook *et al.*, [14] reported reasoning as a predictor of number of moves to complete the Tower of Hanoi. In addition, other cognitive processes have been identified to help solve the Tower of Hanoi such as non-verbal working memory and response inhibition were significant predictors of the number of moves to complete the Tower

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of Hanoi, as well [14]. The number of moves to complete the Tower of Hanoi was also predicted by visuospatial ability and verbal recall [26]. Rönnlund and colleagues also reported visuospatial, verbal fluency and verbal recall predict the average amount of time per move and the number of illegal moves to complete the Tower of Hanoi [26]. These studies demonstrate the complexity of the cognitive abilities needed to successfully complete the Tower of Hanoi task as a measure of non- verbal planning and problem solving in healthy adults.

The prior studies demonstrated that cognitive abilities such as concept formation, response inhibition, processing speed and working memory support Tower of Hanoi performance in healthy adults [13,14,27,28]. However, there little is known about the cognitive abilities that support Tower of Hanoi performance in an adult clinical population with cognitive deficits. Therefore, we decided expand on this line of research by investigating the cognitive influences of the Tower of Hanoi as a nonverbal planning and problem solving task in a substance use disorder population. Executive dysfunction and problem solving deficits have been well established in individuals with alcohol and drug use disorders [10,29-36]. More specifically, these studies have demonstrated deficits in planning, set shifting, cognitive flexibility, inhibition, fluency within the executive function domain as well as deficits of memory and processing speed. Thus, the present study examined the influence of common neurocognitive domains with composite scores from two executive function domains: concept formation and cognitive flexibility as well as information processing speed and verbal memory on the performance measures of the Tower of Hanoi within a substance use disordered population.

Method

Participants

The sample consisted of 115 men and 76 women entering treatment for a substance use disorder. This sample has been described in detail in prior studies [31,37]. The mean age of the participants was 43.54 (*SD* = 17.50, Range: 18-81) years. Their mean number of years of education was 13.17 (*SD* = 2.95). Sixty three percent of participants met a Diagnostic and Statistical Manual -IV (DSM-IV) criteria for an alcohol abuse/dependence diagnosis; 18% met DSM-IV criteria for a drug abuse/dependence diagnosis; and 19% met DSM-IV criteria for dual alcohol and drug use disorder diagnosis. Exclusion criteria were less than 18 years of age, history of organic brain disorder or psychotic disorder, korsakoff's syndrome, severe dementia, methadone maintenance, serious medical condition that precluded testing, and an inability to read the test materials.

Neurocognitive measures

Below is the description of the Tower of Hanoi Test as well as the description of the four Tower of Hanoi performance measures.

Tower of Hanoi test (TOH): Manual 4 disk version [8]. The TOH required moving a pyramid of 4 disks, stacked in size from the largest on the bottom to the smallest on top, from a start post to one of two other posts which was designated the "goal" post. Participants were given three rules prior to the start of the task: (1) only move one disk at a time, (2) do not place a larger disk on top of a smaller disk, and (3) do not remove any disks from the apparatus. Participants were not given any feedback about the correctness of individual disk moves, but rather worked on the puzzle until the problem was solved or 5 minutes had elapsed. Corrections occurred only in the event of a rule violation, which were infrequent (less than 5.4% of moves). The optimum number of moves to complete the task was 15 moves. Performance measures included the number of moves to completion (TOH Moves), the amount of time to completion in seconds (TOH Time), time per move defined as total time divided by total moves (TOH Time/Move), and the number of rule violations (TOH Errors).

Below are the descriptions of the neurocognitive tasks that were used to produce the four cognitive domain composite scores as predictor variables, which were formed in part based on a previous study with this data set [30]: Concept Formation, Cognitive Flexibility, Information Processing Speed and Verbal Memory. The composite scores were produced by centering the performance measures scores, which were then transformed to z-scores. The z-scores were based on the sample's performance with positive z-scores representing better performance on all neurocognitive measures.

Concept formation composite: The Concept Formation Composite consists of the mean z-scores of the Nelson Modified Wisconsin Card Sorting Test and the Booklet Category Test - Brief Version:

Nelson's Modified Wisconsin Card Sorting Task (WCST) [38] measures concept formation, maintenance of the concept, and the ability to shift concepts. The test consists of 48 stimulus cards that are sorted by color, shape, or the number of items. After each card was sorted, the subject was told whether it was "correct" or "incorrect" to help guide the concept formation and maintain the sorting principle. The cards are sorted for each stimulus until a run of six correct responses was achieved. After a run of six correct responses the sorting rule was changed, without the participant being provided that information. The number of perseveration errors was used for the analysis.

The *Brief Booklet Category Test* (BBC) [39,40] correlates strongly with Halstead's original version [41]. The Booklet Category Test is made up of six subtests, with categorizing rules running throughout each of the subtests. The test requires abstract concept formation, mental flexibility, and abstract problem solving ability in order to categorize the stimuli. Immediately following each of the participants' responses, a correct or incorrect response was provided in order for them to use the feedback to help guide the hypothesis testing. Performance on this test was based on the total number of errors. To estimate the performance of the full version of the Category Test, the total number of errors from this version was multiplied by 2.2 [42].

Cognitive flexibility composite: The Cognitive Flexibility Composite was composed of the mean z-scores from the Stroop Test and Trail Making Test-Part B:

The Stroop Test [43] measures the subject's ability to suppress the automatic responding to the lexical feature of the word in order to attend to the color of the ink of the word (Color). Participants were given three types of trials: name color of ink with X's, congruent trial in which the name of the color and ink color matched (Color Naming), and the incongruent trial in which the meaning of the word and the color of the ink did not match (Color-Word). The number of correct responses within 45 seconds for each trial was recorded. We calculated a response inhibition score without the effect of processing speed. The response inhibition score (Stroop) was calculated by regressing Color-Word on Color Naming and subtracting the unstandardized residual score for each participant from the sample's Color-Word mean score. Subtracting the residual score from the Color-Word score has been shown to be an effective measure of interference independent of processing speed [44].

The *Trail Making Test* [45] is a sub-test of the Halstead Reitan Battery, which is composed of Part-A and Part-B. Part-A requires a continuous line connecting the numbers in sequential order throughout the page. Part-B requires the subject to draw a continuous line connecting letters and numbers in an alternating, sequential order (e.g., 1 to A to 2 to B to 3 to C, etc.) and measures cognitive flexibility while maintaining more than one mental sequence at a time, as well as complex tracking skills [46]. In order to get a measure of mental flexibility independent of processing speed we performed the statistical operation as we performed on the Stroop Color-Word inhibition residual measure. The amount of time to complete Trail-B was regressed on the amount of time to complete Trail-A and the unstandardized residual score was subtracted from the sample's mean Trail-B time.

Information processing speed composite: Information Processing Speed Composite was composed of the mean Digit Symbol Substitution Test (DSST) and the Active-Passive test z-scores:

The *Digit-Symbol Substitution Test* (DSST) [47] measures attention, working memory, and visual-motor speed. The subject was given a key with the digits 1 through 9 paired with symbols. Below the key were three rows of digits with blank corresponding boxes beneath. The task was to correctly draw the corresponding symbols in the empty boxes below each digit. Performance was based on the total number of symbols correctly drawn within 90 seconds.

The *Active - Passive Voice Test* [48] is an assessment of the speed in which the participant correctly categorized the sentence of complex syntactic information. The processing speed measure is the average amount of time to one-hundredths of a second of correct responses.

Verbal memory composite: The Verbal Memory Composite consists of the mean CVLT and Product Recall tests z- scores:

The *California Verbal Learning Test* (CVLT) [49] is a measure of verbal memory. The CVLT was administered in its standard format consisting of the tester reading a list of 16 words (list A) from 4 semantic categories (fruits, spices, tools, and clothing). The dependent measures were the total number of words recalled over 5 learning trials (CVLT).

The *Product Recall Test* [50] is a written memory test in which the subject was shown pictures of everyday items from 5 categories: alcohol, cereals, deodorants, pickup trucks, and soft drinks. Pictures were presented sequentially in random order for 10 seconds each. After presenting all pictures, the participant was asked to recall the items and performance was based on the total number of correct products recalled.

Table 1: Means and standard deviations of neurocognitive measures (N = 191).

Domain	Measure	Mean (SD)	Min	Max
Tower of Hanoi	TOH Time (sec)	120.07 (81.85)	14	300
	TOH Moves	24.48 (10.04)	10	73
	TOH Time/Move	4.87 (4.87)	0.41	73
	TOH Errors	1.51 (2.02)	0	9
Concept Formation	WCST	5.49 (6.61)	0	42
	BBC	33.64 (13.65)	4	62
Cognitive Flexibility	Stroop	35.72 (8.37)	18	66
	Trail-B	101.67 (50.15)	-24	307
Processing Speed	DSST	48.71 (15.89)	4	91
	Active-Passive Test (sec)	3.21 (1.29)	1.28	8.1
Memory	CVLT	44.40 (11.32)	10	66
	Product Recall	9.90 (3.21)	0	15

WCST: Wisconsin Card Sorting Test; BBC: Brief Booklet Category Test; DSST: Digit Symbol Substitution Test; CVLT: California Verbal Learning Test

Table 2: Pearson correlation matrix of the neurocognitive measures (N = 191).

	Tower of Hanoi Performance Measures			
Variables	Time	Moves	Time/Move	Errors
WCST	0.54****	0.23**	0.45****	0.33****
BBC	0.41****	0.1	0.40****	0.37****
Stroop	0.32****	0.08	0.34****	0.19**
Trail-B	0.35****	0.20**	0.25***	0.23**
DSST	0.55****	0.17*	0.54****	0.42****
Active-Passive Test	0.52****	0.14	0.51****	0.32****
CVLT	0.38****	0.13	0.36****	0.31****
Product Recall	0.36****	0.09	0.34****	0.24***

Note: *p < 0.05, **p < 0.01, ***p < 0.01, ****p < 0.0001

Table 3: Results of backward elimination regression analyses of TOH measures and unique variance of composite predictor variables (*N* = 191).

TOH measure	F	R^2	Predictor	Unique Variance	β
Time	39.43****	0.39	Concept Formation	0.05***	0.32
			Cognitive Flexibility	0.02*	0.19
			Processing Speed	0.06****	0.36
Moves	7.75**	0.04	Concept Formation	0.04**	0.24
Time/Move	31.73****	0.34	Concept Formation	0.02*	0.21
			Cognitive Flexibility	0.02*	0.18
			Processing Speed	0.07****	0.39
Errors	23.43****	0.2	Concept Formation	0.05***	0.33
			Processing Speed	0.03**	0.25

Note: *p < 0.05, **p < 0.01, ***p < 0.01, ****p < 0.0001

Procedure

Participants were recruited at their respective treatment facilities. All participants provided written informed consent. The neuropsychological battery was administered within 1-2 weeks following treatment entry. If participants required detoxification, "treatment entry" was defined as admission to the treatment program following detoxification. These testing procedures have been shown to yield psychometrically and clinically stable neuropsychological test scores [51].

Results

Means, standard deviations, and the range of raw scores of the neurocognitive measures are shown in table 1. For variables with outliers (TOH time per moves, TOH errors, and Trail Making Test - Part A and Part B), we used the method described by Tabachnick & Fidell [52] to adjust the scores of outliers in order to not lose the data.

The Pearson correlations between the TOH measures and the neurocognitive test scores are shown in table 2. TOH Time, TOH Time/Move, and TOH Errors were significantly correlated to WCST, BBC, Stroop, Trail-B, DSST, Active-Passive test, CVLT, and Product Recall Test with moderate to high correlations. The correlations between TOH Moves and the neurocognitive measures demonstrate small to moderate significant correlations with WCST, Trail-B, and DSST.

In order to examine the relationship of TOH performance measures to each of the composite measures, regression analyses with backward selection were performed to obtain the most parsimonious set of predictors of each TOH performance measure. In addition, due to wide range of ages in the population, age along with all composite measures were entered simultaneously, and predictors with levels of significance greater than .05 were automatically removed from the analyses.

Results for the regression analysis for TOH Time resulted in being significantly predicted by Concept Formation, Cognitive Flexibility, and Speed of Information Processing (R^2 = 0.39, F (3, 183)= 39.43, p < 0.0001). TOH Moves was significantly predicted by Concept Formation (R^2 = 0.04, F (1, 185) = 7.75, p < 0.01). TOH Time/Move was significantly predicted by the Concept Formation, Cognitive Flexibility and Speed of Information Processing (R^2 = 0.34, F (3, 183) = 31.73, p < 0.0001). TOH Rule Violations was significantly predicted by the Concept Formation and Speed of Information Processing Composite (R^2 = 0.20, F (2, 184) = 23.43, p < 0.0001). The beta weights and unique variance proportions for all significant composite predictor variables are shown in table 3. Age was not a significant predictor in any of the models.

Discussion

The present study examined the relationship between the TOH, a measure of nonverbal planning and problem solving, and a common set of neurocognitive constructs in a population of heavy chronic alcohol and substance users entering substance use treatment. The results demonstrate the contributions of concept formation, cognitive flexibility, processing speed, and verbal memory of explained variance on four performance measures of the four-disk TOH.

The results of the correlations between the performance measures of the TOH and the individual neurocognitive measures demonstrated significant positive relationships as expected. The positive relationships demonstrate better performance on the neurocognitive measures were associated with better performance on the TOH measures. The strongest correlations were with the amount of time to solve the TOH and TOH Time/Move with other executive function measures (e.g. WCST, BBC, Stroop, and Trail-B) as well as processing speed measures (DSST and Active-Passive Test) and memory (CVLT and Product Recall). Surprisingly, TOH Moves was only significantly correlated with two of the executive function measures: WCST and Trail-B. Thus, these results suggest the speed to solve the TOH, whether it's the amount of time to complete the task from the beginning or the average amount of time to make each move, has a stronger relationships with the executive functioning, processing speed and memory measures than the level of efficiency (number of moves) to solve the task in this substance use population. The amount of time to solve the task includes the amount of planning time the participant took prior to the first move as well as the planning time in between moves in order to formulate a solution and execute the solution. Thus, time to solve the TOH may be interpreted as efficiency of planning and execution time of a goal.

The results of the regression analyses identified which neurocognitive composites contributed to the performance of the TOH within this substance use population. The two TOH performance measures with the greatest explained variance were TOH Time ($R^2 = 0.39$) and TOH Time/Move ($R^2 = 0.34$) suggest they are the more sensitive performance measures of nonverbal planning and problem solving in comparison to the low explained variance of the models predicting TOH Moves ($R^2 = 0.04$), and Rule Violations ($R^2 = 0.20$). Although prior studies of the TOH have utilized various performance measures, the results of this study suggest time to complete the task (TOH Time) and the amount of time per move (TOH Time/Move) are the best performance measures of nonverbal planning and problem solving in a clinical population with cognitive deficits such as the population used in this study.

The large explained variance for the TOH Time and TOH Time/Moves was due to the executive function domains of concept formation and cognitive flexibility, as well processing speed, but not verbal memory. The relationship between the composite scores and the TOH Time and TOH Time/Moves were positive, as expected. Therefore better performance on the concept formation, cognitive flexibility, and the processing speed composites were related to less time (TOH Time) and less time per move to solve the TOH (TOH Time/Move). Zook and colleagues [14] reported the same relationship with cognitive flexibility and completing the TOH in a healthy young adult population. The TOH is unlike other neuropsychological executive function tests in two ways: first, there are no correct and incorrect responses after each move such as the WCST and Booklet Category Test; and second, it takes a recursive route to solve the puzzle thereby moving a disk back onto the starting post to allow another disk to be placed on the goal post [8]. Thus the results suggest an individual's ability to plan a solution and execute the plan is dependent on concept formation, the ability to identify the abstract relationship among objects or stimuli [53]; as well as cognitive flexibility, and processing speed.

When examining the unique variance of the three significant predictor composites, processing speed had as much unique contribution for TOH Time and TOH Time/Move as the concept formation and cognitive flexibility composites. These results suggest processing speed performance contributes to the amount of time to plan and execute the solution to the TOH in a substance use disorder population. This is consistent with prior studies that have identified processing speed deficits in adults with a substance use disorder negatively affect cognitive efficiency and nonverbal planning and problem solving [10,30,37,51,54].

The study design without a healthy control group provides limitations on interpreting the level of cognitive deficits demonstrated by substance use population. However, the results of this study have implication for future studies. Although common measures were used to predict performance of the Tower of Hanoi, it is unclear how different cognitive measures in the cognitive domains could change results. Despite the limitations, the study has a large sample size with a wide range of ages, types of substance use disorders, and levels of cognitive functioning, which expands this line of research and current understanding of cognitive abilities that impact planning and problem solving.

In conclusions, this study suggest that cognitive remediation of processing speed and executive functioning, especially within the domains of concept formation and cognitive flexibility may improve nonverbal problem solving within a clinical population with cognitive deficits. Ecological validity studies of nonverbal planning and problem solving in neurological populations have demonstrated the relationship between deficits of planning with deficits of being able to perform instrumental activities of daily living and being able to care oneself [3,55,56], as well as employment status [57]. Future studies should explore the effects of cognitive remediation of nonverbal planning and problems solving on self-efficacy and substance abuse/dependence treatment efficacy [58,59].

Author Note

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