Executive Functions Predicting Learning Outcomes in Science & English Language Tasks

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Abstract

The relation of specific executive function (EF) skills to learning tasks was explored. Middle and high school students (N=78) completed a series of tests consisting of two cognitive assessments of EF skills (DCCS and Flanker), a cognitive training video game, and two learning tasks (a chemistry-based simulation exploration task and an English Language Arts comprehension task). Exploratory and intercorrelation analysis indicated a significant correlation of $p < .05$ or a more significant relation of $p < .01$ of both the english and science learning tasks to learners' executive functions. Results indicate that shifting is a better predictor of learning task outcomes than inhibition. However, after controlling for pretest scores and age, inhibition is a better predictor than shifting in the chemistry simulation task only. Moreover, results confirmed a previous finding for the chemistry-based simulation task. These results provide empirical evidence for the importance of executive functions in academic settings and a better understanding of the types of learning tasks that use executive functions.

Introduction

Executive function (EF), referring to the neurocognitive skills involved in self-regulation, is the basis of deliberate, goal-directed behavior. Executive function has been operationally defined as a construct made up of three lower level base functions: inhibitory control, flexible shifting of one's mental frame, and working memory (Miyake, 2000). Inhibition is important for regulating one's behavior, changing one's attention span, and monitoring emotional responses. *Cognitive flexibility* is the ability to change perspectives, the flexibility in responding to changing demands and circumstances, and to the ability to approach a problem from a different point of view. *Working memory* can be visualized as a mental workspace and refers to the holding of information in mind and working with it, primarily when working with time-related events and relating the past to the present. Working memory comes into play when linguistics are concerned, mentally playing with ideas and drawing connections about old ideas, concluding a general principle, and mentally reordering information. These skills help us to plan, organize, and complete tasks. Developing executive function helps us to lead better lives and is found to more indicative of life success than intelligence quotient (IQ), predicting math and reading achievement, as well as success in career, marriage, and positive mental and physical health. A 32-year longitudinal study following 1,000 children born in the same city during the same year found that children whose inhibition is worse between the years 3-11 grow up to have worse health, earn less money, be less happy, and commit more crimes 30 years later compared to those who had better inhibitory (self-control) control as children. The study concluded a linear relationship between inhibitory control and resulting outcomes (Moffitt et al., 2011). Inhibition (self-control) can be measured by quantifying observations using a scale, often based on the perception of the studied participant, perception of friends and family, and perception of certified examiners. In Moffitt et al., 2011, measures of self-control varied with age. Children's self control in the first decade of their life were measured using a multi-occasion/multi-informant strategy, consisting of a composite measure of an overall self-control predicted by nine measures including observational ratings of children's lack of control, parent and teacher reports of impulsive aggression, and parent, teacher, and self reports of hyperactivity, lack of persistence, inattention and impulsivity. Inhibition can also be measured by having a child participate in a testing session involving cognitive and motor tasks in which examiners evaluate the child's lack of control. In young adulthood, self-control was measured through informant and self-reports, in which people nominated by the participant were mailed the Big Five Personality Inventory (BFI) (John & Srivastava, 1999) and participants measured their perception of self-control through the Self-Control scale of Multidimensional Personality Questionnaire (MPQ) (Patrick et al., 2002).

Executive Function in Academic Settings

In recent years, there has been a growing interest in the importance of executive function towards the positive development of children, because they are a better indicator of school readiness than intelligence quotient (Diamond et al., 2007; Blair & Razza, 2007; Duckworth & Seligmann, 2005), and will predict academic outcomes, school success, and overall life success. A growing body of literature has suggested executive functions to be the underlying processes to early learning, acting as a foundational base that promotes learning (Blair & Raver, 2015; Raver et al., 2011; Blair & Razza, 2007). The relationship between EF and learning is of particular interest when concerned with children with poor executive functioning and who experience widening achievement gaps compared to their peers. Of notable research is the income-related achievement gap. Research has shown lower-income children to have worse executive functioning than their higher-income peers (Blair & Razza, 2007; Diamond et al., 2007; Weatherholt et al., 2006) This disparity has been suggested to be a likely cause to achievement gaps between lower-income and higher-income children. Additionally, children with impairments in EF find a growing difficulty in functioning in school and this challenge often manifests in various clinical conditions such as ADHD. To this end, targeting and training EF is critical for school success, and can avert widening achievement gaps.

Trainability of EF

Children are born with a base-level of executive functioning capacity, associated with their socioeconomic status and attachment relationships (Zelazo et al., 2012) and the ability to develop these as they grow up. Executive functions are malleable and seem to be more so during “sensitive periods” of the brain in which the brain grows particularly fast. These “sensitive periods” where the brain is rapidly adapting to increasing pressure and a changing environment coincide with preschool years when children face increasing demands on EF during the transition to school, and the years transitioning from childhood to adolescence. Early intervention has shown to lead not only to behavioral improvements, but also changes in neural function. This malleability of EF has led to research on how best to train EF, whether through indirect or direct training approaches. Direct training involves repetitive practice on a specific EF task hoping to get better at that task. Indirect training involves training on activities that exercise EF, such as learning mathematics or martial arts, in which becoming better at that activity is the goal.

Several early-education programs have been designed with the intention to foster self-regulation and have resulted in favorable academic outcomes, especially for low-income children (Blair & Raver, 2015; Raver et al., 2011; Blair & Razza, 2007, Riggs et al., 2006). Raver et al. (2011) implemented a self-regulation program known as the Chicago School Readiness project and improved low-income children’s self-regulation skills, measured through attention and impulse control, and showed significant benefits for pre-academic skills such as vocab, letter-naming and math skills. The PATHS curriculum (Riggs et al., 2006) promoted inhibitory and verbal fluency through a social-emotional developmental program. Blair & Razza (2007) was able to show that the inhibitory control and cognitive flexibility of EF account for unique variance in academic outcomes independent of general intelligence and that inhibitory control prominently correlates to both math and reading ability. Blair & Raver (2015) confirms these findings of self-regulation enhancing children’s engagement learning and establishing academic trajectories and adds on to show positive outcomes on EF, reasoning ability, increase in reading, vocab, and mathematics at the end of kindergarten that translated into first grade. Programs have been shown to have a generally positive effect on children. High-quality pre-K and kindergarten programs emphasizing child-directed learning and exploration such as Tools of the Mind (Bodrova & Leong, 2007) and Opening the World of Learning (Schickedanz & Dickinson, 2005) have also shown increases in EF, and through EF, higher levels of academic ability. Students may benefit from a curriculum that fosters the growth of cognitive skills over school practices that promote standardized testing (Finn et al., 2014). This suggests the importance of targeted interventions that build EF skills.

Executive Functions Related to Learning Tasks

Prior research has established strong empirical relations between EF and academic outcomes, notably in early math ability (Epsy et al., 2004; Bull & Scerif, 2001) and literacy (Blair & Razza, 2007; Hooper et al., 2002). Research on preschool readiness showed that EF skills including inhibition, cognitive flexibility, and working memory predict science readiness more strongly than mathematics, and mathematics more strongly than vocabulary and listening (Nayfeld, Fuccillo, & Greenfield, 2013). Additional neuropsychological processes including oral language and executive function account for variance in reading comprehension (Sesma, Mahone, Levine, Eason & Cutting 2008; McCardle et al., 2001; Catts et al., 1999; Swanson, 1999; Nation & Snowling, 1998; Scarborough, 1990), and children who exhibit adequate reading accuracy, but have difficulty in reading comprehension demonstrate the most prominent weakness in EF (Cutting et al., 2009). Deficits in EF have been shown to lead to learning difficulties in math and reading (Altemeier et al., 2006; Cutting et al., 2009; McLean & Hitch, 1999; Swanson, 1999). However, the question remains: which academic tasks are related to specific executive functions?

Previous work has shown, for example, that EF moderates the effectiveness of exploratory science simulations versus worked out simulations (Homer & Plass, 2014). This study showed that simulation exploration, in which learners choose their own path to investigate a science simulation, is effective for the study of the *Ideal Gas Laws* for students with high executive functions, whereas the use of worked simulations, in which the path of exploration is predetermined by an expert science teacher, is more beneficial to low executive function learners. Working memory, one of the core EFs, has been shown repeatedly to correlate with math and reading ability among 5- and 6- year olds (Alloway & Alloway, 2010) and among 11- and 12- year olds (St-Clair Thompson & Gathercole, 2006) and predicts mathematics and science achievement among adolescents (Gathercole et al., 2004). Alteimer et al. (2010) adds to previous findings (Hooper et al., 2002) that EF contributes to the writing development of elementary-grade students and is needed in the integration process of reading-writing; reading a source material, taking notes, and converting those notes into a written report, but notes that EF contributes more to the integration process of reading-writing than each academic domain alone. Inhibition was shown to contribute to the note-taking task because of the need to inhibit redundancy and to inhibit less important details and select the most important and relevant details. Other evidence suggests that working memory is a significant predictor of reading comprehension, while inhibition is not (Christopher, Miyaki, Keenan, et al., 2012). A meta-analytic review identified a significant and moderate relationship between EF and reading comprehension ($r = .36$, $p < .001$) (Follmer, 2017). A more detailed analysis of the specific EF measures used suggests that working memory and shifting were the most prevalently correlated measures with reading comprehension, while inhibition showed the most variability. Another study involving traditional, exam, and charter public schools and covering a wide socioeconomic range identified a significant and moderate correlation between ELA and EF skills of working memory, processing speed, and fluid memory (Finn, Kraft, & West, 2014). This indicates that specific executive functions contribute to different reading-writing tasks at hand and learning tasks.

The objective of the research is to expand the knowledge of which tasks are predicted by a learners' EF skills. To that end, a science simulation exploration task and an English language learning tasks were included to study possible relationships between specific EF skills and learning tasks.

Method and Data Sources

Participants

This study was done in accordance to the institutional IRB guidelines. The participants for this study were recruited from middle and high schools in New York City and New Jersey. Out of 78 students, 37 identified themselves as female, 36 identified as male, and 5 did not respond to the prompt. Participants' ages ranged from 12 to 17 years (M = 14.32, SD = 1.4 years).

Materials

Two cognitive assessments, a cognitive training game, and two learning tasks (LT) were used in this study. All materials were delivered on a computer screen, except for a paper-based packet used during the Gas Laws Simulation LT. The two cognitive assessments were the Dimensional Change Card Sorting (DCCS) task and the Flanker task. The cognitive training game, Gwakkamole, was played on the DREAM platform, a platform developed by CREATE Lab. The following two tasks are widely used measures of executive function suitable for use across the lifespan and are used in this study as cognitive assessments:

The Dimensional Change Card Sorting (DCCS) task. The DDCS task adapted from (Zelazo, 2006) prompts participants to sort through a series of bivalent test cards, according to dimension stated on the screen, "shape" or "color." A prompt "color" or "shape" would appear in the middle of the screen, followed by a ball or truck, in either yellow or blue. Participants were instructed to select one of two images at the bottom corners of the screen matching the dimension stated. For logistic purposes, the right arrow key corresponded to the image on the right corner. The left arrow key corresponded to the image on the left corner. A practice session following mostly the same set of rules was administered to participants before the actual task but used a different set of images. The practice session was completed at participant's own time, while the actual session was timed. Participants were instructed to complete the task as quickly and accurately as they can without making mistakes. They were also instructed beforehand to continue the task in the event a mistake was made. If no image was selected in The task requires participants to shift their focus between contrasting features, to tap into cognitive flexibility, and to avoid negative priming.

Flanker task. The NIH Toolbox Flanker task adapted from (Zelazo et al., 2014) showed participants a row of five arrows pointing left or right randomly. The goal was to press the arrow key corresponding to the center arrow as quickly as possible. Participants were instructed to complete the task as quickly as accurate as they can without making mistakes and to continue in the event a mistake was made. The task requires participants to inhibit their attention from the alternative arrows surrounding the target and make an accurate selection quickly. It is a measure of inhibitory control and selective attention.

The following two tasks were used as learning tasks:

The first *learning task* was an exploratory simulation of the Ideal Gas Laws previously developed and used in (Homer, 2014) with a pretest and a posttest of content knowledge, and a posttest for transfer knowledge. The simulation showed a container of gas particles with sliders responsible for three variables: temperature, pressure, and volume. The exploratory model of the Ideal Gas Laws simulation is highly interactive and requires participants to formulate and test their own hypothesis by adjusting a slider responsible for one variable. To the right of the container of gas particles is a chart plotting results from the simulation. Content knowledge was twenty-one multiple choice questions, while transfer knowledge items were four open-ended responses to gauge transfer of knowledge from the simulation to real-world scenarios. The multiple choice questions were scored as pass/fail, with one point for each correct answer. The transfer items were scored independently by two research assistants, using a pre-determined grading rubric. Participants were able to gain up to two points for each open response answer. After reaching an inter-coder reliability of .96, the scores were averaged, and a percentage (correct items out of total items) was created for scoring and analysis. Participants were provided with a paper packet containing a comic-strip narrative and questions to guide their exploration of the Gas Law Simulation.

The second *learning task* comprised of test items from the English New York Regents

Examinations. Two passages and the associated questions were chosen from tests older than five years to avoid prior exposure for the older participants in the study. Participants were given fifteen minutes to complete this task.

Procedure

A researcher explained the study and obtained informed consent forms from participants before starting. The researcher then remained present to answer any questions. Participants were tested individually at computer workstations in a lab setting. All students completed a battery of tests that were broken up into three blocks of tasks. The first block consisted of completing two cognitive pretests relating to inhibition and shifting EF skills, Flanker task and DCCS task respectively, playing 20 minutes of a cognitive training game, followed by two cognitive post-tests, the same as the pre-tests. The second block consisted of students taking a Gas Laws pretest, interacting with the exploratory version of the *Ideal Gas Laws* simulation, then completing a Gas Laws post-tests. The third block consisted of an excerpt of two passages from an English NYS Regents Examination.

Results

The DCCS and Flanker tasks were scored on a 0-10 point scale according to the NIH Toolbox guidelines, with a higher score representing better performance. The LTs (Learning Tasks) were scored as a percentage of the total possible for each task. An exploratory factor analysis (EFA) of the data revealed six outliers whose EF posttest scores were less than half of their pretest scores; 4 DCCS posttest, and 2 Flanker posttest scores were removed from the dataset. The final dataset contained 73 complete observations. An intercorrelation analysis revealed that EF measures, Age, and GL pretests had a significant correlation with LTs (Table 1) and were included as control variables for partial correlations.

Gas Law Simulations and Comprehension

A correlation analysis indicates the Gas Law Comprehension post-test scores (GLC) are significantly correlated with both DCCS Post-test scores ($r(74) = .302$, $p < 0.01$), and Flanker Post-test scores ($r(73) = .288$, $p < .05$). A partial correlation, controlling for Gas Law pre-test scores and age (Table 2) indicates that Flanker Post-test performance has a significant relationship with Gas Law post-test scores ($r (60) = .233$, $p < .05$). The partial correlation also indicates that DCCS performance is not significantly correlated with Gas Law Comprehension scores ($r(60) = .172$, $p = .091$). The partial correlation indicates that inhibition (Flanker score) accounts for 5.4% of the variance in GLC scores.

Gas Law Simulations and Transfer

Correlation analysis also indicates the Gas Law Transfer post-test scores (GLT) are significantly correlated with both DCCS Post-test scores ($r(74) = .392$, $p < .001$), and Flanker Post-test scores ($r(73) = .318$, $p < .01$). A partial correlation, controlling for Gas Law pre-test scores and age (Table 3), indicates that Flanker Post-test performance has a significant relationship with GLT scores ($r(60) = .240$, $p < .05$), while DCCS Post-test performance is not significantly correlated with GLT scores ($r(60) = .085$, $p = .255$). The partial correlation indicates that inhibition (Flanker score) accounts for 5.7% of the variance in GLT scores.

Reading Comprehension

Correlation analysis indicates that Reading Comprehension (RC) scores are significantly correlated with both DCCS Post-test scores ($r(74) = .474$, $p < .001$) and Flanker Post-test scores ($r(74) = .372$, $p < .001$). A partial correlation controlling for age (Table 4) indicates significant and small to moderate correlations with DCCS Post-test scores ($r(61) = .29$, $p < .05$) and Flanker Post scores ($r(61) = .30$, $p < .01$). The partial correlation indicates that shifting (DCCS) accounts for 8.4% of the variance in RC while inhibition accounts for 9%.

Discussion

This study investigated the relationship between executive functions and specific learning tasks. We were interested to know the extent of what types of science and English language tasks are related to learners' executive functions. Thus a simulation task was included to see if previous findings of "all students, regardless of their level of EF, showed better transfer of knowledge after interacting with the exploratory simulation" (Homer & Plass, 2014) could be confirmed. This finding was replicated in this study, with students performing significantly better on executive functioning tasks (DCCS and Flanker) after interacting with the exploratory simulation. These results agree with instructional approaches that emphasize interactivity for deeper levels of learning and provide empirical evidence for computerized training in EF. Students were required to inhibit distractions to stay on task in the Gas Laws simulation, update working memory with new information gathered to draw relationships between the Gas Laws, and shift to different rules when different aspects of the simulation are explored (e.g. the relation of temperature and volume versus the relation of pressure and volume). While both Flanker (inhibition EF task) and DCCS (shifting EF task) are significantly correlated with Gas Law Simulations Transfer knowledge, Flanker (inhibition) was shown to account for a larger variance than DCCS (shifting) after controlling for Gas Laws pre-test scores and age. However, when relating Gas Laws comprehension questions to specific executive functions, inhibition (Flanker) correlates significantly with comprehension questions while shifting (DCCS) has no significant correlation. Moreover, inhibition accounts for 5.4% of the variance in Gas Laws comprehension scores. In the Gas Laws exploration simulations, inhibition seems to play a stronger role than shifting in gaining content knowledge (comprehension questions) and in the application of content knowledge (transfer questions).

The English language learning task required learners to read a passage in English, then respond to comprehension questions. The ELA task required the learner to inhibit distracting ideas and alternative engagement, to shift their attention to different features of the task, and keep in active working memory the content of the passage. Results indicate that a learner's' performance on the ELA task is predicted by the level of their EF skills. Reading comprehension scores were significantly correlated to both DCCS and Flanker with inhibition (Flanker) accounting for 9%

of the variance in reading comprehension and shifting accounting for 8% in reading comprehension. The results suggest that reading comprehension uses the executive functions of shifting and inhibition to relatively similar degrees regardless of age.

The results support a relationship of learning tasks to specific executive function skills. Comprehension after using the Gas Laws Simulation, a science simulation exploration task, utilizes working memory, cognitive flexibility, and inhibition, but outcomes are governed more by inhibition. Transfer knowledge after using the Gas Laws Simulation uses working memory, cognitive flexibility, and inhibition, and overall relies more on cognitive flexibility, but show improvements in inhibition after being trained. The English language task outcomes show that inhibition, cognitive flexibility, and working memory contribute significantly to outcomes, with shifting (cognitive flexibility) accounting for more of the brain process.

Limitations and Future Directions

The present work was conducted with middle and high school students in a large urban area. Additional research is required to determine whether the findings extend to rural and suburban schools, to other age groups, and across different academic domains other than science and literacy. The study could have been executed with a better design. Participants reported experiencing fatigue, and as a result, several observations had to be removed for being outliers. Another major weakness of this study is that EFs overlap to a certain extent and contribute to the well-known task impurity problem. Although it has been shown that inhibition, shifting, and working memory are moderately correlated with each other, these three EFs are clearly separable (Miyake, 2000). However, it is unclear whether the low correlation among these EFs on complex executive tasks is a conclusive reflection of the independence of the three EFs or if cognitive processes, other than the target executive functioning skills, are contributing to the executive task. Thus non executive processing may mask commonalities among the EFs and indicate a lack of correlations among executive functions. The task impurity problem is elevated further because participants often take different strategies on different occasions or within sessions. Executive control functions are strongest and most active when the task is novel, so repeated encounters with the task may reduce its effectiveness in actually capturing the target executive process, thereby yielding low reliability (Miyake, 2000). This is in agreement with the results, which show EF pretests to correlate stronger with learning tasks. Perhaps the baseline EF, as measured through EF pretests, are more predictive of learning task outcomes. At the same time, participants were given a 20-minute EF training game. 20 minutes is not long enough to witness a substantial gain in EF, and if the time setting were to be extended, then a greater change in EF is likely to be witnessed, leading to better ability to learn as measured through the learning tasks. Further directions include a better experimental design to reduce fatigue and boredom in participants and a longer time setting for training EF game (or a longitudinal study). Also, interesting finds such as if a baseline EF is more important than other measurements of EF in predicting learning task outcomes should be addressed. Additional analysis can separate participants into those with a higher EF baseline and those with a lower EF baseline, using the average score on the pretests as a divider, to draw further conclusions. Since there is a significant correlation between EF and learning tasks, the next step is a more extensive study training EF to lead to academic outcomes. The results from this study confirm a relationship of executive functions and learning task outcomes, particularly in the science and English Language arts domain.

Conclusion

The results of this study expand the knowledge of which tasks are predicted by learners' EF levels and reconfirms EF as a predictor of academic achievement. There is a significant correlation between both english language arts learning task and science simulation exploration task to a learners' executive functions. In the science simulation exploration task, inhibition seemed to be a stronger predictor of gaining content knowledge and the application of content knowledge than shifting. In the ELA learning task, results indicated that reading comprehension uses both inhibition and shifting to relatively similar degrees. These results highly suggest that EF as a predictor of learning tasks.

This research is of theoretical and practical significance. On the practical side, these findings provide empirical evidence to support the importance of EF in academic settings, especially in ELA and science, and furthered the understanding of the kinds of learning tasks that require mastery of EF skills. On the theoretical side, the study provided insights into the types of learning tasks that tap into executive functions. Such examination of specific executive functions and learning tasks is critical to understanding underlying neuropsychological processes that promote school readiness. Given the value of EF in the positive development of children, these findings have important implications for developing a minimal expense educational curriculum to nurture the academic and long-term success of students.

Appendix A: Tables

Table 1. Intercorrelations of all measures

		Age	DCCS Score Post	Flanker Score Post	Gas Law Pre-Percent (GLP)	Gas Law Post-Percent (GLC)	Gas Law Transfer (GLT)	Reading Comprehension Percent (RC)
Age	Pearson Correlation	1	0.173	0.190	0.286*	0.341**	0.139	0.320**
	Sig. (2-tailed)		0.155	0.120	0.014	0.003	0.240	0.006
	N	73	69	68	73	73	73	73
DCCS Score Post	Pearson Correlation		1	0.396**	0.415**	0.302**	0.392**	0.474**
	Sig. (2-tailed)			0.001	0.000	0.009	0.001	0.000
	N		74	73	74	74	74	74
Flanker Score Post	Pearson Correlation			1	0.267*	0.288*	0.318**	0.372**
	Sig. (2-tailed)				0.023	0.014	0.006	0.001
	N				73	73	73	73
GLP	Pearson Correlation				1	0.456**	0.105	0.274*
	Sig. (2-tailed)					0.000	0.362	0.015
	N				78	78	78	78
GLC	Pearson Correlation					1	0.419**	0.518**
	Sig. (2-tailed)						0.000	0.000
	N					78	78	78
GLT	Pearson Correlation						1	0.482**
	Sig. (2-tailed)							0.000
	N						78	78
RC	Pearson Correlation							1
	Sig. (2-tailed)							
	N							78

* significance level: $p < 0.05$
** significance level: $p < 0.01$

Table 2. Gas Law Comprehension partial correlations

GLC Correlations					
Control Variables			GLC	Flanker Post	DCCS Post
GLP & Age	GLC	Correlation	1.000	0.233	0.172
		Significance (1-tailed)	.	0.034	0.091
		df	0	60	60
	Flanker Post	Correlation		1.000	0.475
		Significance (1-tailed)			0.000
		df		0	60
	DCCS Post	Correlation			1.000
		Significance (1-tailed)			.
		df			0

Table 3. Gas Law Transfer partial correlations

GLT Correlations					
Control Variables			GLT	DCC Post	Flanker Post
GLP & Age	GLT Percent	Correlation	1.000	0.085	0.240
		Significance (1-tailed)	.	0.255	0.030
		df	0	60	60
	DCCS Post	Correlation		1.000	0.475
		Significance (1-tailed)		.	0.000
		df		0	60
	Flanker Post	Correlation			1.000
		Significance (1-tailed)			.
		df			0

Table 4. Reading Comprehension partial correlations

RC Partial Correlations					
Control Variables			RC Percent	DCCS Post	Flanker Post
Age	RC Percent	Correlation	1.000	0.290	0.300
		Significance (1-tailed)	.	0.011	0.009
		df	0	61	61
	DCCS Post	Correlation		1.000	0.488
		Significance (1-tailed)		.	0.000
		df		0	61
	Flanker Post	Correlation			1.000
		Significance (1-tailed)			.
		df			0

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