Can Fluency Predict Problem Solving Behavior in Knowledge-lean Puzzles?

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January 2014

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Samenvatting

Deze studie onderzoekt de relatie tussen de executieve functie van fluency en probleemoplossend vermogen in zogenaamde knowledge-lean puzzels. Fluency wordt ook wel aangeduid als cognitieve flexibiliteit, dan wel effectief strategiegebruik. De verwachting is dat hoog fluente participanten beter zijn in het aanpassen van leerstrategieën wanneer de taak dit noodzakelijk maakt, en meer succesvol in het genereren van relevante hypothesen tijdens het probleemoplossende proces. Fluency is daarmee naar verwachting een effectieve voorspeller van zowel flexibiliteit in het gebruik van probleemoplossende strategieën, als in hypothesegeneratie, en is naar verwachting effectiever in het voorspellen van resultaten dan andere dominant gemeten executieve functies, zoals werkgeheugen en inhibitie.

Deze studie werd uitgevoerd op locatie bij de East China Normal University (ECNU) in Shanghai, China. Dataverzameling werd gerealiseerd door middel van een experiment waarin scores op knowledge-lean puzzels en executieve functie tests (Figure Fluency Test, Word Fluency Test, Colour Word Interference Test, en WISC-getallenreeksen) aan elkaar werden gerelateerd. Respondenten (n = 53) zijn allen student (gemiddelde leeftijd = 19.3 jaar, SD = 1.07, n = 53, 18 mannen en 35 vrouwen).

Figuurfluency voorspelt succes op de probleemoplossende taak, F (1, 51) = 5.568, p = .022, R2 = 0,081 mede door een verhoogd gebruik van de experimentruimte, F (1, 51) = 17,623, p <.001, R2 = .242, dit blijkt een effectieve voorspeller van succes in probleem oplossen in knowledge-lean puzzels. Tenslotte voorspelt figuurfluency de uniciteit in succesvolle oplossingen, F (1, 51) = 9.412, p = .003, R^2 = .156. Hoogfluente participanten geven meer originele, succesvolle oplossingen.

De resultaten indiceren dat fluency gemiddeld tot hoog gecorreleerd is aan probleemoplossend vermogen in knowledge-lean puzzels. Hoogfluente participanten experimenteren meer, genereren betere hypothesen en zijn flexibeler in hun probleemoplossende strategieën. De resultaten laten zien dat het voorspellend vermogen van fluency uniek verbonden is aan deze executieve functie, daar werkgeheugen en inhibitie geen voorspellend vermogen laten zien. Participanten lijken cognitieve flexibiliteit te gebruiken wanneer het gebruik van geheugenstrategieën niet leidt tot resultaat, waarbij hoogfluente participanten een verhoogd oplossend vermogen tonen. De resultaten steunen de hypothesen en valideren de conclusie dat fluency een effectieve voorspeller is in probleemoplossend gedrag in knowledge-lean puzzels.

Abstract

This study investigates the relation between the executive function of fluency and problem solving ability in knowledge-lean puzzles. Fluency is also referred to as cognitive flexibility or effective strategy use. It is expected that highly fluent learners are better able to adapt learning strategies when needed, and are more successful in generating relevant hypotheses during the problem solving process. Fluency thus is to be an effective predictor of both flexibility in strategy use and hypothesis generation ability, and is to be more effective in predicting these results than other dominantly measured executive functions such as working memory and inhibition.

The fieldwork of this study was conducted on location at the East China Normal University (ECNU) in Shanghai, China (2012). Data gathering was executed by means of an experiment in which computerized knowledge-lean puzzles and executive function tests (Figure Fluency Test, Word Fluency Test, Colour Word Interference Test, and WISC-digit span) were related and evaluated. Participants (n=53) are all undergraduate students (mean age = 19.3 years, *SD* = 1.07, *n* = 53, 18 men and 35 woman).

Figure fluency predicts success in the problem solving task, F (1, 51) = 5.568, p = .022, R2= .081 partly due to more elaborate use of the experiment space, F (1, 51) = 17.623, p < .001, R2= .242, which shows to be an effective predictor of problem solving success in knowledge-lean puzzles. Finally, figure fluency predicts uniqueness in successful solutions, F (1, 51) = 9,412, p = .003, R2= .156. Highly fluent participants provide more original successful solutions.

Our results show that fluency is correlated moderately-to-high to problem solving ability in knowledge-lean puzzles. Highly fluent participants show increased experimenting, provide better hypotheses and are more flexible in their problem-solving strategies. Results show that fluency can uniquely and effectively predict these results as compared to working memory and inhibition, which show no predictive capacity. Participants seem to rely on cognitive flexibility when other strategies do not lead to desired results. These problem-solving abilities, based on flexibility in the use of strategy, is predominantly seen in highly fluent participants. Based on these results, our hypotheses are validated. These results support our hypotheses and validate the conclusion that fluency effectively predicts problem-solving behavior in knowledge-lean puzzles.

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Introduction

Recent developments in the field of education address the importance of adaptive instruction in the classroom (Jonassen & Grabowski, 2012). Individuals differ in their learning, and thus in their educational needs (Fischer & Daley, 2006; Fischer et al., 2010). Still, most of the global educational systems share knowledge in a static manner and therefore fail to address individual learning preferences (Fischer & Daley, 2006; Fischer et al., 2010). Individuality in learning requires attention and with restricted instruction time and limited means in the classroom, the question that comes to mind is how to guide learners effectively and efficiently. Accepting the urge for adaptive instructions demands specific guidelines in order to shape this instruction. Which learner characteristics are diagnostic in performance and behavior has to be determined. Developments in the field of the cognitive neurosciences may assist in identifying relevant learner characteristics and may provide insight as to how and why these characteristics are predictive of learner ability and behavior. Although some scholars argue that using insights from this field have not yet matured enough to be used to explain concrete learner behavior (Bruer, 1997; Klahr, 2011), evidence to the contrary has been reported as well (Goldstein & Naglieri, 2014; Van Klink, Eysink & De Jong, Submitted).

One of the principles which has been investigated in relation to instruction and learning is Executive Functions (EF). These are multiple distributed neural networks that include the thalamus, basal ganglia, and prefrontal cortex of the brain (Pennington 2002; Welsh et al., 2005), and are necessary for higher cognition such as problem solving (P. Anderson, 2003; V. A. Anderson, 1998; Best, Miller, & Jones, 2009; Zimmerman, 2007). ‘Executive functions’ is an umbrella term for functions essential for complex behavior such as planning and mental flexibility (Anderson, 1998; Chan et al. 2008; Garon, Bryson & Smith, 2008; Best et al., 2009). They are the core skills that regulate our thoughts and actions by means of self-regulation or cognitive control (Blakemore, 2012) and play an important role in overall higher order learning processes (Anderson, 1998; Anderson, 2003; Best, Miller, & Jones, 2009). Recent findings support the claim that the EF can predict learning outcomes in specific educational settings (Van Klink et al., Submitted). Although there is some controversy as to which specific functions the executive functions entail, there is widespread consensus among researchers on the validity of fluency, inhibition and working memory as unique interpretable executive functions (Best et al., 2009; Jurado & Rosselli, 2007; Miyake et al., 2000).

Fluency is considered the cognitive flexibility, or shifting, which enables us to think creatively (Rabbitt, 2007). Literature described this flexibility as the mental ability to switch between thinking about two or more different concepts simultaneously. Fluency is defined as the ability to adapt easily and use strategies effectively (Goldstein & Naglieri, 2014). Scott (1962) defined cognitive flexibility as “the readiness with which the person's concept system changes selectively in response to appropriate environmental stimuli.” According to Jurado & Rosselli (2007), inhibition reflects the individual ability to inhibit stimuli and behavior. It functions as a restraint on an otherwise natural and spontaneous thoughts and/or actions. In learning it enables learners to focus on relevant information (the data presented) by suppressing irrelevant information (e.g., prior beliefs). Working memory is defined as a hypothetical limited capacity system that provides the temporary storage and manipulation of information that is necessary for performing a wide range of cognitive activities (Baddely, 2012).

Studies investigating the relation between the EF and learning can be divided into two categories: first, studies focusing on enhancing learning by training the EF; second, studies using EF to identify strengths and weaknesses, with the goal to use these learner characteristics to choose the most effective learning strategy. Application of the second approach strives towards using adaptive instruction and matching it with learner characteristics. Although this line of research seems promising, some scholars point out that, in order to be able to use insights from the field of neuropsychology to enhance learning, concrete cognitive models which predict concrete learner behavior based on learner characteristics are essential (Klahr, 2011). These models have not yet been reported.

In this study we focus on investigating whether the executive functions, specifically fluency, can effectively predict learner results and behavior in the context of problem solving. We do so with the intent to start formulating the cognitive models needed to guide adaptive instruction, to optimize learning. Because the executive functions actively guide behavior in tasks that are new and rely on not (yet) automated responses (Rabbitt, 2007), we explore problem solving in the context of knowledge-lean problems for which prior knowledge is not relevant (Robertson, 2008). In addition to the advantage of having new problem settings for all subjects, knowledge-lean problems also entail having clear solutions with all possible successful paths known beforehand. Analyses of behavior during problem solving therefore can concentrate on strategies used. A further rationale for focusing on knowledge-lean problems is that these problems are suited to created isomorphs relatively easily, thus providing the opportunity to study potential changes in strategy-use (Robertson, 2008). This is important in our investigation because fluency is defined as the ability to adapt easily and use strategies effectively. We expect that, when faced with a set of problems in which the use of one dominantly applied strategy does not work (such as trying to remember all options), learners with high fluency scores, are better able to deal with this challenge (ineffective strategy-use) by adapting their learning strategy. Knowledge lean problems provide the opportunity to investigate this hypothesis. In this study we therefore will investigate problem solving in isomorphic knowledge lean problems, and relate outcomes to executive function test scores. We will use puzzles for which strategy changes are needed in order to succeed and expect to find that fluent learners will score better due to adaptive capacity. In order to differentiate between high fluency scores and other executive function scores (discriminant validity), inhibition and working memory will be measured as well.

In addition to the expectation that fluent learners are better able to adapt when faced with ineffective learning strategies, we expect that highly fluent learners are better able to organize the problem solving process by means of effective hypotheses generation during problem solving. Because fluency is related to creativity and originality (Milgram & Arad, 1981; Milgram, 1983; Shaw & Demers, 1986; Runco & Charles, 1993; Runco & Chand, 1994; Runco & Illies & Eisenman, 2005) it is expected that highly fluent learners are better able to come up with multiple hypotheses. Learners often hold on to one (initial) hypothesis during problem investigation, even when results do not support this hypothesis (De Jong & Van Joolingen, 1998). It is expected that fluent learners are better able to adapt both strategies and held hypotheses during the problem solving process, thus leading to better results.

In summary, this study investigates the relation between the executive function of fluency and problem solving in knowledge-lean problems. It is expected that highly fluent learners are better able to adapt learning strategies when needed, and that they are more successful in generating relevant hypotheses during the problem solving process. We therefore expect to find that fluency is an effective predictor of both flexibility in strategy use and of hypothesis generation, and is more effective in predicting these results than other dominantly measured executive functions (working memory and inhibition).

Method

The fieldwork of this study was conducted on location at the East China Normal University (ECNU) in Shanghai, China. During five consecutive weeks in fall 2012, data gathering was executed by means of an experiment and executive function testing.

Participants

The respondents are all undergraduate students at the East China Normal University. A total of 53 students (mean age = 19.3 years, *SD* = 1.07, *n* = 53, 18 men and 35 woman) voluntarily participated in the study.

Materials

Five different tests were used in this experiment. Four tests were used to measure executive functioning reflecting fluency (word- and figural-), inhibition and working memory. The fifth test is a problem-solving task based on a knowledge-lean puzzle principle, designed for this experiment.

Fluency

Fluency was administered using the Word Fluency Test (WFT) and the non-verbal Figure Fluency test (FFT) (Ruff, Light, Parker, & Levin, 1997). Both measure the ability to rapidly produce a particular kind of response based on a given stimulus. The WFT measures verbal fluency by addressing the participants' ad hoc knowledge of a certain semantic category. Two categories – animals and professions – were administered, each provided with a sixty-seconds time limit (Tombaugh, Kozak & Rees, 1999). The FFT addresses the participants' cognitive ability to produce unique patterns. This non-verbal test reflects figural fluency. The participant is asked to produce as many unique patterns as possible. He or she is given a restricted timeframe to connect five dots using only straight lines. The number of correct unique patterns determines the score.

Inhibition

Inhibition was measured using the Delis Kaplan Executive Function System Color Word Inference Test (CWI). The CWI III is based on the Stroop-Test paradigm for measuring inhibition (Homack, Lee, and Riccio, 2005; Delis, Kaplan, & Kramer, 2008a; Delis et al., 2008b). The CWI contains four subtests: Color naming, Reading words, Inhibition, and Inhibition/switching (Delis et al., 2008a). The completion time on the CWI-inhibition subtest expresses the ability to suppress an automatic response in order to produce a conflicting response (Delis et al., 2008a) and was used as a measure of inhibition.

Working memory

WM was measured using the Digit Span subtest of the Wechsler Intelligence Scale for Children (Wechsler, 1991). The backward scores were administered. Scores on the 'backward' (Digit-BW) items are most indicative of working memory capacity (Baron, 2004) because this score relies on the ability to manipulate the information kept in memory. The test scores used in analyses represent raw test scores on Digit-BW (number of items correct).

Problem solving

We explore problem solving in the context of knowledge-lean puzzles. In these puzzles prior knowledge is not relevant and objects and rules are clear (Robertson, 2008). In order to measure problem solving in a knowledge-lean context, we developed a computerized puzzle. This task, (see Figure 1) describes a ‘cave quest’ in which the participants are confronted with a cave door which leads to the sought after treasure.

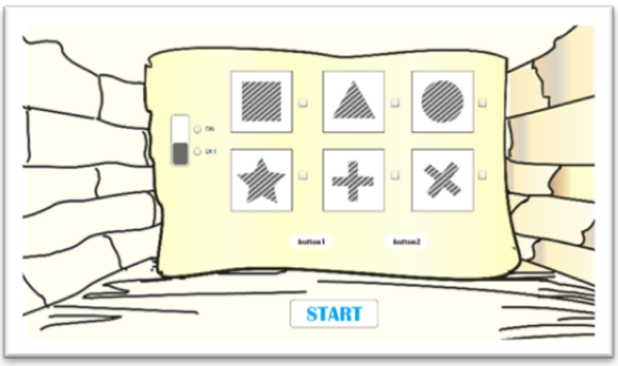

Figure 1. The cave experiment reflecting the problem solving task in the experiment

Note: solution subtask 1: off, star, triangle, cross, button 1; solution subtask 2: off, square, plus, circle, button 1; solution subtask 3: every solution that contains a star, plus and cross.

The cave door is locked and can only be opened by entering a specific code. In line with the knowledge-lean characteristic of having all the possible successful paths known beforehand (Robertson, 2008), the code can only be entered using the buttons and handle on the door panel. The panel consists of (1) a handle which can be switched on or off, (2) six buttons resembling abstract figures, which all can be switched either on or off, and (3) two buttons, respectively button 1 and button 2. In the latter participants can select either button 1 or 2. The amount of selectable options is supposed to indicate to the participants that memory is insufficient in remembering all experiments. After a selection has been made the participants need to press the 'start' button to see whether the door will open. Three subsequent doors have to be opened in order to find the treasure (3 subtasks).

The task has a time limit of ten minutes per subtask in which participants can experiment with different combinations (experimenting phase). This refers to the strategies in knowledge-lean puzzling. The results of this experimenting are registered in the program log files and are scored afterwards on both correctness (scored 0 if the door did not open, and 1 if the door did open), and uniqueness (based on whether a the entered combination was entered before: 1 for each unique correct answer). In addition, the total number of experiments conducted was scored as well. In order to assess whether highly fluent learners are better able to organize the problem solving process by means of effective hypotheses generation, we scored a 'hypothesis generation'-measure 0, 1 or 3. Participants needed to formulate a hypothesis before each experiment (prior to each possible solution). Non-related hypothesis scores 0 – this ranges from writing non-existing words, notating numbers and/or a non-task related statement – and a hypothesis that reflected the learning task is awarded 1 point. These hypotheses are characterized by modestly targeted statements, which are task-related and focused on an outcome. Further, hypotheses that both reflected the learning task and provided a clear goal-directed solution and/or predicting value are rewarded 3 points.

The first two subtasks contain one possible solution: a complex combination of all the accessible buttons. In the third subtask each combination results in success when at least the lower three abstract buttons are selected. This way the participants are enabled in providing a wide range of successful solutions. The uniqueness in successful answering is measured in the third task in order to discriminate between individuals who are more successful due to increased tries versus individuals who are more successful due to creativeness by deploying more original answering.

Procedure

Tests were administered in one, 55 minutes, session. The session started with a 5-minute instruction, followed by a 30-minute knowledge-lean puzzle (10 minutes per subtask), and subsequently fluency, working memory and inhibition were tested in an additional 20-minute timeframe (WFT, FFT, WISC-Digit Span and CWI). The participants received a standardized verbalized instruction. This explained the rules and options of the learning task as well as the overall procedure. Additionally they were provided with an instruction manual, containing the same instruction (Annex). The participants were informed on the possibility to consult the instruction manual whenever desired. All tests were written in Chinese and administered by educational technology students who had been trained on the procedures.

Results

The main research question of this study addressed the predicting ability of the executive functions on problem solving in knowledge-lean puzzles. The executive functions measured in this study are fluency, working memory and inhibition. Fluency is suggested to influence problem solving ability in knowledge-lean puzzles. Both working memory and inhibition are expected to have no predicting ability. Fluency is measured both individually (WFT/FFT) and combined (FLU =WFT+FFT). The combined score is a summing up of both fluency (WFT/FFT) measures and is used due to general factor desirability – as with the other executive functions. As table 1 shows, the found correlations indicate strong relations between fluency and task results. Working memory provides a significant correlation on task success in the first task. No further significant effects on working memory are shown by the results. Inhibition does not show any significant effect in all subtasks. Fluency does persistently show significant correlations. Especially figure fluency, as expected given the visual nature of the task. In the first and second task there is low 'space' for fluency. The results show that the number of tries has a positive effect on successfulness and that this is achieved by unique (original) answering.

Table 1

Correlations of the experimenting on fluency, working memory and inhibition

Measure	S1	S2	S3	U3	SP1	SP2	SP3	FLU	WF	FF	INH	WM	HYP
S1	1												
S2	.386**	1											
S3	.155	.566**	1										
U3	.218	.562**	.920**	1									
SP1	.266	.484**	.586**	.559**	1								
SP2	.230	.197	.490**	.512**	.715*	1							
SP3	.112	.053	.276*	.288	.581**	784**	1						
FLU	.184	.215	.407**	.362**	.471**	.554**	.516**	1					
WF	.043	.020	.240	.175	.226	.400**	.319*	.744*	1				
FF	.259	.294*	.428**	.395**	.507*	.530**	.523**	.942**	.478**	1			
INH	.085	.246	.231	.215	.215	.266	.247	.073	.022	.087	1		
WM	.319*	.136	.047	.060	.036	.050	.029	.109	.267	.010	.032	1	
HYP	.138	.112	.030	.008	.001	.144	.161	.306*	.271*	.262	.093	.037	1

S1: success in subtask 1; S2: success in subtask 2; S3: success in subtask 3; U3: unique successful answers subtask 3; SP1: utilization experiment space subtask 1; SP2: utilization experiment space subtask 2; SP3: utilization experiment space subtask 3; WF: Word Fluency Test, FF: Figure Fluency Test; INH: Color Word Interference Test - subtest 3; WM: Wechsler Intelligence Scale for Children (WISC) - Digit Span Test - backwards. $^*p < .05$, $^{**}p < .01$.

In determining the causality of the correlations multiple regression analyses were run to predict task success and hypothesizing by fluency, word fluency, figure fluency, inhibition and working memory.

Table 2

Multiple (stepwise) regression analysis

Predictor Variable	R^2	Adjusted R^2	B	SE B	*B*	*t*	*p*
Success	.183	.167					
Constant			-6.737	3.483		-1.934	.059
FF			.111	.033	.428	3.378	.001
Space	.273	.259					
Constant			-	10.261		-2.006	.050
FF			.425	.097	.523	4.379	.000
Unique	.156	.139					
Constant			-3.190	2.156		-1.479	.145
FF			.063	.020	.395	3.068	.003
Hypothesis	.094	.076					
Constant			-.406	.281		-1.445	.154
WF			.004	.002	.306	2.297	.026

B: un-standardized beta coefficient, SE B: standard error, β: standardized beta coefficient, WF: Word Fluency Test, FF: Figure Fluency Test; Success: success in subtasks; Space: utilization experiment space; Unique: unique correct solutions; Hypothesis: hypothesis generation scores.

In order to identify which executive function has the most predictive value and to explore whether a second and third added executive function has additional predictive power, stepwise versions of the regression analysis were performed. Three separate regressions were deployed with in succession ‘success’, ‘space’ and ‘uniqueness’ as the dependent variable. The stepwise regression procedure provides one explaining factor for each dependent variable, as table 2 shows. Figure fluency statistically significantly predicts success on the problem solving task, F (1, 51) = 5.568, p = .022, R2= .081. Other executive functions indicate no influence. Furthermore, FF statistically significantly predicts the used experiment space, F (1, 51) = 17.623, p < .001, R2= .242. Highly fluent participants utilize the experiment space to a higher extent and this is a statistically significant predictor of success on the learning task. Finally, figure fluency statistically significantly predicts uniqueness in successful solutions, F (1, 51) = 9,412, p = .003, R2= .156. Highly fluent participants provide more original successful solutions. The results show that highly fluent students are more successful in their problem solving due to the fact that they provide more answers and that this extended experimenting results in risen problem solving success based on increased originality.

Discussion

In this study we investigated the relation between the executive function of fluency and problem solving in knowledge-lean puzzles. It was expected that highly fluent learners are better able to adapt learning strategies when needed, and are more successful in generating relevant hypotheses during the problem solving process. We therefore expected to find that fluency is an effective predictor of both flexibility in strategy use and of hypothesis generation, leading to better results. We also expected that fluency is more effective in predicting these results than other dominantly measured executive functions (working memory and inhibition).

Our results show that fluency is correlated moderately to high, to the number of experiments conducted in all 3 subtasks. Inhibition and working memory are not significantly correlated to the number of experiments conducted. This indicates that highly fluent participants were more active during the experimenting phase. Furthermore, highly fluent participants demonstrate better hypothesizing, reflected in a moderate correlation between fluency scores and hypothesis generation, although this does not result in risen success in problem solving or increased originality.

Results further demonstrate that highly fluent participants score better at subtasks 2 and 3, as compared to little fluent participants (moderate correlations between fluency scores and both ‘good’, and ‘unique good’ answers for both subtasks). For subtask 1, participants with high working memory scores conducted better results. These findings indicate that for the first task, relying on working memory helped solving the task, but for task 2 and 3 this strategy proved less successful. This can be explained because the task was developed to challenge working memory capacity in the many experiments that could be conducted. Highly fluent participants dominantly scored on the 2nd and 3rd subtask. This may be explained because of altered strategy use between subtask 1 and 2, when confronted with the realization that the task exceeded working memory capacity. Highly fluent learners were better able to change their strategy to tackle this problem, thus leading to more success in the subsequent subtasks.

Although these conclusions are promising, they are speculative in nature without further research. Results here validate our hypotheses, but more insight has to be gathered now in the actual thinking process during problem solving. Because this study is explorative in nature, and restricted in time and means, no further investigations were conducted as to this purpose.

Regression analysis further shows that fluency uniquely (in combined analyses with both inhibition and working memory) predicts both success in the problem-solving task, as well as the amount of experiments conducted, and hypothesis generation. Based on these results, our hypotheses are validated. These results, though explorative in nature, support the conclusion that fluency effectively predicts problem-solving behavior in knowledge-lean puzzles.

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