The Two-Factor Structure of Cognitive Flexibility: Tempo of Switching and Overcoming of Prepotent Responses

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ABSTRACT

The current study aimed to uncover the structure of common latent processes underlying the execution of several tasks that hypothetically measure spontaneous and adaptive cognitive flexibility, providing evidence for their convergent validity. A group of healthy volunteers (*N* = 121) completed two sets of tasks to assess spontaneous and adaptive cognitive flexibility. Spontaneous flexibility measures included a divergent thinking test (to assess fluency and flexibility of thinking) and a verbal fluency test. Adaptive flexibility measures involved a set-switching test as a measure of switch costs and an attentional set-shifting test as a measure of learned irrelevance and perseveration). A vocabulary knowledge test provided a proxy measure of crystallized intelligence. Hierarchical cluster analysis using Ward's method revealed the existence of two separate subgroups of variables. The first group comprised fluency and flexibility of thinking, crystallized intelligence, verbal fluency, and switch costs. The second group included attentional shift variables, that is, learned irrelevance and perseveration. We consider these results meaningful and indicative of two separate factors contributing to cognitive flexibility: (a) speed of switching and (b) overcoming of prepotent responses. We discuss the implications of our results for the assessment of cognitive flexibility.

KEYWORDS

spontaneous cognitive flexibility
adaptive cognitive flexibility
divergent thinking; task-switching
attentional set-shifting

INTRODUCTION

The notion of cognitive flexibility (CF) refers to a disposition to adapt behaviour to new situations or to changing circumstances (e.g., Cañas et al., 2003; Lezak, 1995; Önen & Kocak, 2015). This cognitive ability (e.g., Bennett & Muller, 2010; Diamond, 2006; Lezak, 1995; Muller et al., 2015) or a core executive function (e.g., Diamond, 2013; Gabrys et al. 2019; Glass et al., 2013) contributes to many higher-order processes, such as creativity and problem solving (e.g., Beghetto & Kaufman, 2007; Bennett & Muller, 2010; Guilford, 1967; Hennessey & Amabile, 2010; Kudrowitz & Dippo, 2013; Nusbaum & Silvia, 2011; Runco & Acar, 2012), learning (e.g., Cañas et al., 2006; Feng et al., 2020), decision making and communication (Martin & Rubin, 1995). However, studies on CF avail themselves of different measurement methods, such as divergent thinking tasks (in creativity studies), the Wisconsin Card Sorting Test (in neuropsychology), or task-switching (in cognitive psychology). Although this methodological diversity should, in theory, increase the generalizability of the results to a construct level, it actually makes the knowledge on CF fragmented, precluding any transfer of conclusions from one field to another. Thus, advances in CF research may, pivot on the development of a consistent operationalization of CF (Dajani & Uddin, 2015). However, to our knowledge, only a few studies (Eslinger & Grattan, 1993; Filippetti & Krumm, 2020) have examined the factor structure of CF tests to determine overlap in cognitive abilities that contribute to cognitively flexible behaviour. These results suggest that a single mechanism is insufficient to explain the heterogeneous nature of CF. Following this research path, in this study, we aimed to determine the degree to which the CF tasks measure the same latent construct or multiple separate constructs, using (a) a broader collection of CF diagnostic methods and (b) Guilford's model of CF as a theoretically plausible structure of the examined variables. Table 1 presents the methods of CF assessment used in different studies.

The tasks in the first group are used in neuropsychological assessment of CF. They include the Wisconsin Card Sorting Test (Berg, 1948; Milner, 1963), the Trail Making Test B (Bowie & Harvey, 2006; Reitan, 1958), and verbal fluency test (Benton, 1968; Lezak et al., 2012). The Wisconsin Card Sorting Test is the most popular tool in clinical diagnosis. It requires participants to sort cards according to either colour, shape, or number

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TABLE 1.
The Methods to Measure Cognitive Flexibility Used by Different Research Areas

Research area	Example tasks	Description	Mechanisms
Neuropsychology	Wisconsin Card Sorting Task. Dependent variables: set loss and perseverative errors.	The task is to match cards with a given example card; participants have to determine the sorting criterion by themselves based on feedback.	Working memory operation, error detection, feedback utilization, concept formation/rule inference, attentional set-shifting, attentional set-maintenance; (Lie et al., 2006).
	Trial Making Test B. Dependent variables: reaction times (RTs) and errors.	The test form presents 25 circles, which include numbers (1 – 13) or letters (A – L); participants connect the circles with lines in ascending order, alternating between numbers and letters (i.e., 1-A-2-B,…).	Visual search, switching mental set, executive control, motor control; (Bowie & Harvey, 2006).
	Verbal or semantic fluency. Dependent variables: number of items generated.	Generation of words from a given category within a preset time (e.g., 60 seconds).	Memory search and category recall inhibition to avoid perseverative errors, attention, updating and working memory processes (Azuma, 2004).
Cognitive neuroscience, cognitive psychology	Attentional set-shifting task. Dependent variables: accuracy and RT on switch trials; number of trials performed before a shift due to a rule change is achieved.	Participants learn a set of rules in a series of discriminations of compound stimuli; once learned, the rules change, requiring participants to change attentional-set (including shifting attention to another feature of a stimulus); different shifts are possible, for example, reversal shifts, intra-, and extra-dimensional shifts.	Working memory operation, concept formation/ rules inference, attentional set-shifting, attentional-set maintenance, error detection, and feedback utilization (Hampshire & Owen, 2005).
	Task switching. Dependent variables: switch costs (differences between RT of alternations and repetitions).	Participants perform two tasks (e.g., categorizing letters or numbers) that are performed on bivalent stimuli, in repetitive or alternating order.	Instantiating representations, preparing task-specific processes and monitoring response selection and execution; switch costs relate to endogenous control processes reconfiguring the cognitive system; alternatively exogenously triggered processes resolving interference in task execution (Vandierendonck et al, 2010).
Creativity	Divergent thinking.	Participants respond to open-ended questions; the responses are scored in terms of fluency (number of responses), flexibility (diversity), originality (uniqueness) of thinking, and so forth.	Multiple ideas generation affected by semantic memory search and retrieval processes, bottom-up and top-down attention, and cognitive control (Benedek et al., 2017).

of elements depicted and then switch between the rules, exhibiting flexibility and concept formation. Trail Making Test B measures mental flexibility, processing speed, and visuomotor skills. Finally, verbal fluency measures semantic or letter fluency, including perseverative errors (e.g., Lezak, 1995; Ritter et al., 2012). These tasks are very complex, and it is difficult to identify the underlying cognitive processes that they engage.

The second related group of tasks is most often used in an experimental context to study executive functions. It includes attentional set-shifting (e.g., Downes et al. 1989; Owen et al., 1993; Slabosz et al., 2006) or task-switching (Jersild, 1927; Meiran, 1996; Pashler, 2000; Rogers & Monsell, 1995) paradigms. The attentional set-shifting task was modelled after the Wisconsin Card Sorting Test as a less confounding version. It distinguishes several specific forms of attentional switches, such as intradimensional or extradimensional set-shifts. Intradimensional shifts concern switching within any category such as colour or shape, for example, from red to green stimuli (Downes et al., 1989). Extradimensional shifts consist in moving attention between categories or dimensions, for example, between digits and letters. These shifts can be due to learned irrelevance shifts (LI) or perseveration (PE). LI refers to an inability to attend to information that was irrelevant at the previous stages of the task (i.e., to information not associated with a reward, Mackintosh, 1975; Owen et al., 1993; Slabosz et al., 2006). In contrast, PE reflects a difficulty in disengaging attention from a previously relevant (rewarded) aspect of a stimulus (while ignoring new features), even though they no longer fulfil the task requirements (e.g., Dreisbach & Goschke, 2004; Gruszka et al., 2010; Owen et al., 1993).

The task-switching paradigm requires multiple transitions between similar tasks (Monsell et al., 2000; Rogers & Monsell, 1995; Steinhauser & Steinhauser, 2019) performed on univaent or bivalent stimuli (stimuli that can be categorized within either task). The switching costs reflect the time needed to change task sets, that is, to reallocate attention from one task-set to another and flexibly switch categorization rules (Meiran, 1996; Rogers & Monsell, 1995)

The third group of tasks measures CF in the context of creative thinking as its fundamental aspect (e.g., Beghetto & Kaufman, 2007; Guilford, 1967; Hennessey & Amabile, 2010; Kudrowitz & Dippo, 2013; Nusbaum & Silvia, 2011; Runco & Acar, 2012) because CF requires the ability to generate alternative solutions or behaviours. Creativity and CF are measured by

TABLE 2.
The Methods to Measure Two Types of Cognitive Flexibility

Authors	Adaptive flexibility	Spontaneous flexibility
Filipetti and Krumm (2020)	(Reactive flexibility)	
	Tasks/indicators	
	Wisconsin Card Sorting/the number of completed categories Trail Making Test-B/reaction time and the number of errors	Creative thinking test/fluency, elaboration, originality Verbal Fluency Test/the number of correct words given for each subject
	Explanation of the existing two types	
	Only inhibition contributed to adaptive flexibility (reactive flexibility)	Working memory and inhibition contributed to spontaneous flexibility
Eslinger and Grattan (1993)	Tasks/indicators	
	Wisconsin Card Sorting/the number of errors	Alternate Uses Test/the number of object's uses generated
	Explanation of the existing two types	
	Frontal lobe and basal ganglia damage each caused a similar degree of impairment in adaptive flexibility (reactive flexibility)	Frontal lobe damage resulted in markedly distorted spontaneous flexibility
Boot et al. (2017)	(Stability)	(Flexibility)
	Tasks/indicators	
	Switching/attentional shifts and updating	Divergent thinking
	Explanation of the existing two types	
	Prefrontal dopamine and the integrity of the mesocortical dopaminergic pathways were associated with stability (persistent) processing	Flexibility processing was associated with dopaminergic pathway.

TABLE 3.
The Classification of the Indicators of Cognitive Flexibility Included in the Current Study

Spontaneous flexibility		Adaptive flexibility	
Task	Indicators	Task	Indicators
Verbal fluency task	Verbal fluency	Task task-switching	SC crosstalk SC no-crosstalk
Divergent thinking task	Fluency DT Flexibility DT	Perseveration and learned irrelevance task	PE compatible LI compatible PE incompatible LI incompatible

divergent thinking tasks, such as alternative uses or remote consequences (Guilford, 1967). The tasks require the generation of as many answers as possible in response to a cue (e.g., Beghetto & Kaufman, 2007; Carson et al., 2005; Guilford, 1967; Hennessey & Amabile, 2010; Kudrowitz & Dippo, 2013; Nusbaum & Silvia, 2011; Runco & Acar, 2012). The number of generated ideas indicates thinking fluency. The number of generated categories of ideas indicates the flexibility of thinking. Originality (the number of rare solutions) and elaboration (the ability to expand on an idea and adorn it with details) indicate the level of creativity.

It is not entirely clear whether all the methods described above measure a common latent construct of CF because their relationship is not well-defined and seems understudied. Guilford (1967) indicated that the tasks might measure different forms of CF, singling out two types of CF: spontaneous and adaptive. Spontaneous CF underlies original ideas, while adaptive CF concerns the change of strategy in response to a changing environment. Furthermore, Eslinger and Grattan (1993) suggest that different neural structures may mediate the two types of CF. Spontaneous flexibility (i.e., generation of diverse ideas) was present in patients with frontal-lobe lesions, suggesting that new ideas require direct cortical-cortical interactions. The frontal lobes allow access to novel strategies to generate new semantic linkages. By contrast, adaptive flexibility was mediated by the frontal lobe, basal ganglia, and their interconnections, implying the operation of the corticostriatal system (Eslinger & Grattan, 1993).

A slightly different perspective on CF and brain mechanisms was proposed by Boot et al. (2017). It relies on a dual-path model of creativity (Nijstad et al., 2010). According to Boot et al. (2017), moderate (but not low or high) levels of striatal dopamine enhance creative cognition by facilitating switching between activities or perspectives, divergent thinking (switches between categories), remote associations, or the adoption of a broad attentional scope. Prefrontal dopamine, mediated by the mesocortical pathways, affects creative persistence. Thus, moderate prefrontal dopamine levels enable systematic analytical processing, convergent thinking, increased and prolonged mental effort, and the generation of multiple novel ideas within a given category. However, Boot et al. (2017) have not tested their proposal empirically.

Finally, a recent series of two studies by Filippetti and Krumm (2020) revealed the structural model of cognitive flexibility in children, composed of two forms of flexibility: adaptive (based on indicators from the Wisconsin Card Sorting Test and the Trail Making Tests) and spontaneous (based on indicators from a design generation task). Both forms of flexibility contribute differently to reading, writing, or creativity. They also impose different demands on working memory and cognitive inhibition in studied groups.

The results obtained by Eslinger and Grattan (1993) and Filippetti and Krumm (2020), as well as the hypotheses forwarded by Boot et al. (2017) suggest that a single mechanism is insufficient to explain the heterogeneous nature of flexibility measures and underlying brain function (see Table 2). Therefore, in this study, we aimed to examine whether the proposed classification of CF measures reflects a latent structure of the variance on a different population than those studied by Eslinger and Grattan (1993) and Filippetti and Krumm (2020), using a different set of tasks. Additionally, our classification considered additional indicators of CF such as perseveration and LI. We hypothesized that divergent thinking indices and verbal fluency would refer to spontaneous CF whereas task-switching and attentional set-shifting variables would represent adaptive CF (see Table 3).

METHOD

Participants

One hundred twenty-one healthy adults from a job recruitment portal and social media platform participated in this study (M_{age} = 28.2, *SD* = 5.3; 25 males, at least 12 years of formal education). Participants received 40 PLN (~9 €) upon finishing the study. The committee for ethics in studies involving human participants at the Institute of Psychology in Poland approved this study. In accordance with the Helsinki declaration, participants signed written informed consent forms.

Tasks and Materials

VERBAL FLUENCY TASK (ŁUCKI, 1995)

The participants listed as many words that belong to an indicated category as possible within one minute, including animals, words starting with the letter "k," and sharp objects. The score amounts to the mean number of items generated in each category (Łucki, 1995). The reliability of the verbal fluency task measured with Cronbach's αwas 0.66 in the current study.

DIVERGENT THINKING TASK (DT; NĘCKA & RYCHLICKA, 1987)

The participants generated responses to an open-question problem within 5 minutes (e.g., "What is a fork like?"). The fluency DT reflects the number of ideas generated. The flexibility DT amounts to the number of response categories assessed in the following way. Each answer is classified according to the following three dimensions: (a) as general (G; applying to the entire subject or all exemplars) or fragmentary (F; referring to a part of an object or a given item), (b) visual (V; relating to the appearance of the item) or functional (Fu; relating to the function of the object), and (c) analogous (A; relating directly to an object) or metaphorical (M; using metaphor). Combining the three dimensions creates eight possible categories of responses (e.g., GVA, FVA, or GFuA). The number of observed response categories provides an index of flexibility. The value of Cronbach's αcoefficient for this task in our study was 0.52.

TASK-SWITCHING PARADIGM (ROGERS ET. AL., 1998)

In this task, each trial started with the presentation of a stimulus. Depending on the current task condition, participants decided whether a digit is even or odd or a letter is a vowel or consonant. After a speeded reaction (hitting the response button), a new trial was presented in which the displayed stimulus changed. The color of the display indicated the current task: green implied responding to digits, while red – responding to letters. The color of the board changed every two trials regularly and predictably, indicating a task change.

The task consisted of two conditions: no-crosstalk and crosstalk. This manipulation refers to the observation that switching from one task to another is more difficult if a stimulus that activates the currently inappropriate task is still present on display (Rogers & Monsell, 1995). It always included two items: (a) a letter and a digit (e.g., A3) or (b) a letter or a digit and a neutral mathematical character (e.g., A% or 3%). In the no-crosstalk version, the stimulus irrelevant to the current task always belonged to a neutral category (i.e., it did not interfere with a correct answer). However, in the crosstalk manipulation, in most cases (77% of trials), the irrelevant character belonged to the category that invoked an incorrect response, while in the remaining 33%, it belonged to the neutral set. Both conditions consisted of two training blocks followed by four experimental blocks of 40 trials each. There were short breaks between the individual blocks. Participants could proceed to the next block by pressing the space bar on the computer keyboard. The first character pair of the next block appeared 2 s later. After each trial, an intertrial interval of 1 s followed before the next character pair was presented. Switch costs were measured as an increase in reaction time (RT) observed when comparing switching between tasks to continuous performance of the same task, calculated separately for the crosstalk and no-crosstalk conditions. In the current study, the value

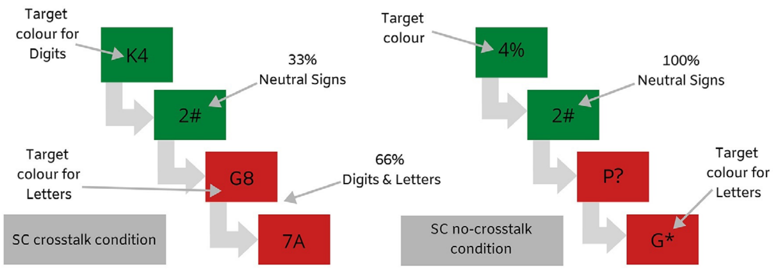

FIGURE 1.
A schematic representation of the switch task in the switch costs (SC) crosstalk and no-crosstalk conditions based on Rogers et.al. (1995).

of Cronbach's αcoefficient for switch costs in the crosstalk and no-crosstalk conditions in our study was 0.86. It took about 15 minutes to complete the task (see Figure 1).

PERSEVERATION AND LEARNED IRRELEVANCE TASK (PE AND LI TASK, DREISBACH & GOSCHKE, 2004)

In each trial, two stimuli – either two digits or two letters – were presented on a screen one above the other. Participants decided whether an integer was even or odd and whether the letter was a vowel or consonant. The colour of stimuli informed the participants whether they should respond to the digit or the letter.

There were two experimental manipulations concerning the type of shift (PE or LI) and the type of display (compatible or incompatible). In the LI condition, participants switched to the color that characterized a distractor in the former trial. Thus, to overcome LI, participants had to shift the response set to the familiar (but previously irrelevant) dimension, ignoring the novel dimension. In turn, in the PE condition participants switched to the new color while distractors appeared in the formerly relevant color. To overcome PE, the participants had to ignore the previously relevant dimension. Target stimuli and distractors were either compatible or incompatible (see Figure 2). In the first case, they required the same response (e.g., both stimuli were even numbers). In contrast, the target and the distractor could activate two different reactions (a vowel and a consonant) in the incompatible condition. Each trial started with a fixation cross (250 ms). It was followed by a blank screen (250 ms) and then the stimulus, which remained on the screen until a response was given. Then, the screen remained black (1 s) until the beginning of the subsequent trial. After 40 trials, a cue (2 s) indicated the target color. Eight practice trials (4 blocks of switching between digits and 4 blocks of switching between letters) preceded the main task. It consisted of six blocks: three blocks of the LI condition and three blocks of the PE condition, each comprising of 60 trials. Each block consisted of 60 trials. After the first 40 answers of a block, the target color changed.

The performance was assessed by calculating a difference in RTs between two blocks: before and after the color change for each of the conditions of the task: LI compatible, LI incompatible, PE compatible, PE incompatible. The Cronbach's αfor this task was 0.49 in the present study. The task lasted about 20 minutes.

VOCABULARY KNOWLEDGE TEST (CHOYNOWSKI, 1977)

The test provides a measure of crystallized intelligence. Participants chose a word with the same meaning as a reference word out of four options. They were granted a time limit of 5 minutes to complete the task, which consisted of 40 items. The number of correct answers indicated the performance level. Considering the link between verbal working memory and crystallized intelligence (Haavisto & Lehto, 2005), the vocabulary knowledge test was used for control purposes to ensure that intelligence was not responsible for the observed relationships amongst CF indicators, especially verbal fluency and divergent thinking.

Procedure

The study was conducted in the Institutes of Psychology in Cracow, Opole and Wroclaw. It was advertised through social media, and the volunteers applied by e-mail.

The study was conducted individually. A single study session lasted approximately 90 minutes. In the first step, the participants were presented with information about the subject and purpose of the study. The researchers informed participants about the possibility of withdrawing from the study at any time and the conditions for remuneration. Then, participants signed the informed consent form and the form on the protection of personal data. Participants completed the measures in the order described in the Materials and Tasks section. The study was a part of a larger research project to understand the relationships between temperament and cognitive flexibility.

RESULTS

Given the normal distribution of the obtained data, statistical analyses were performed using the correlation matrix method in R Studio. We also carried out a hierarchical cluster analysis using Ward's method with Euclidean distance, performed in IBM SPSS Statistics 26. The hierarchical cluster analysis results were validated using the random split method.

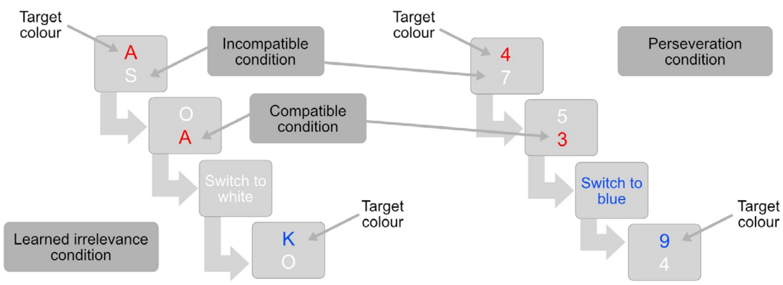

FIGURE 2.

A schematic representation of perseveration and learned irrelevance task based on Dreisbach and Goschke (2004). White, red and blue stimuli represent switch conditions. In the learned irrelevance condition, a distractor in the subsequent trials appears in the new colour (here bulue). In the perseveration condition, the new colour is blue, and distractors appear in the formerly relevant colour (here white). For compatible conditions target stimuli is consistent with distractor, for incompatible conditions target stimulus is inconsistent with distractor.

Correlations Between Indicators of Spontaneous CF

First, we tested the hypothesis that divergent thinking indices and verbal fluency would refer to spontaneous CF. We found these correlations to be positive and statistically significant. The highest correlation occurred between verbal fluency and fluency DT (r = .39, p < .01) and flexibility DT (r = .36, p < .01). We also observed a moderate positive correlation between verbal fluency and crystallised intelligence (r = .35, p < .01, see Table 4).

Correlations Between Indicators of Adaptive CF

Next, we ascertained if the variables from task-switching and attentional set-shifting paradigms represent adaptive CF. Our analysis did not reveal any link between attentional set-shifting indices and switch costs measured by the task-switching paradigm. This observation indicates that there was no postulated similarity between indicators of adaptive CF. Several positive within-task correlations were noted between indicators of PE and LI in the attentional set-shifting task only, which presumably reflect a common RT factor (see Table 4).

Relationships Between Adaptive and Spontaneous CF and Crystallized Intelligence

We also performed a correlational analysis of the methods representing the two types of CF (see Table 4). The indices of spontaneous and adaptive flexibility were not statistically significantly correlated.

We also included the vocabulary knowledge test that measures crystallized intelligence to control for a possible factor that may have contributed to correlations amongst the variables representing CF. Crystallized intelligence correlated with verbal fluency (r = .37, p < .01), fluency DT (r = .20, p < .5), and flexibility DT (r = .24, p < .01). There was also a positive relationship between crystallized intelligence and scores in the PE incompatible condition (r = .26, p < .01) and the PE compatible condition (r = .31, p < .01).

Ward Hierarchical Clustering Analysis

In the subsequent step, we performed a hierarchical cluster analysis using Ward's method (Ward, 1963) to search for relationships amongst the indicators of CF included in the current study. We included crystallized intelligence in the cluster analysis, as it correlated with several measures of CF. As a result, we identified two main clusters, as shown in the dendrogram (see Figure 3). Cluster 1 was composed of switch-cost, verbal fluency, flexibility DT, fluency DT, and crystallized (verbal) intelligence (vocabulary knowledge test). Within Cluster 1, three base tier subclusters formed from the combination of within-task indicators: task set-switching (crosstalk with no-crosstalk), divergent thinking task (fluency DT with flexibility DT), and the two verbal tests (vocabulary knowledge test and verbal fluency task). The first two of these subclusters (task set-switching and the divergent thinking task) merged into a superior tier, and then both verbal fluency tests entered into the final Cluster 1. Cluster 2 comprised LI and PE in the compatible and incompatible conditions.

This two-cluster stratification was then validated using the method of random split of participants into two groups (Blashfield, 1980; Hillhouse & Adler, 1997). We obtained identical results as described above, which was indicative of their reliability.

DISCUSSION

In the current study, we identified relationships between several tasks measuring CF. Our analysis revealed that the spontaneous CF variables, that is, fluency DT, flexibility DT, and verbal fluency are correlated (from r = .36 to .39). This observation provides a compelling argument for the external validity of the tested methods and the notion of spontaneous CF. However, the ezed to belong to adaptive CF did not group as expected. Indeed, the observed correlations between switch costs and LI or PE indicators were weak (from r = −.13 to .12) and not statistically significant. These results are not indicative of the notion of adaptive flexibility. However, low-strength correlations between tasks may or may not reflect the lack of a common underlying construct, but may result from other factors. For example, as discussed by Schmiedek et al. (2014), such low-strength correlations could be caused by task-specific or content-specific sources of variance, measurement error, or restrictions of range (e.g., floor or ceiling effects). These sources of variance should be excluded before concluding that the tasks measure distinct constructs.

We next applied cluster analysis to identify distinct, homogeneous assemblies of variables. This method was appropriate in a sample of the size recruited for this study. Given that the vocabulary knowledge test index of general intelligence correlated with many indices of CF, it was included into this analysis. It revealed the existence of two clusters of variables. The first cluster was very inclusive, consisting of most of

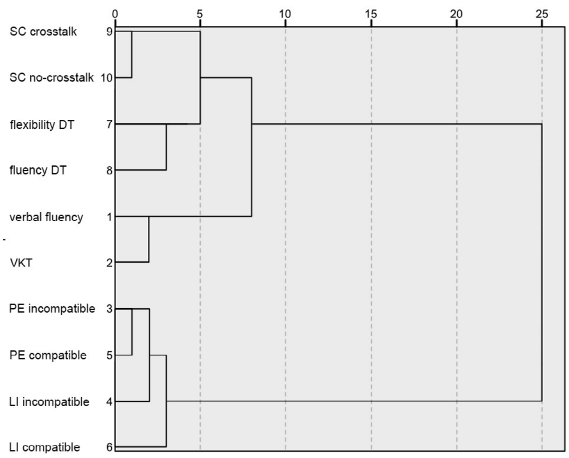

FIGURE 3.

The results of hierarchical cluster analysis using Ward's method (Ward, 1963). Task indicators are shown on the left: task-switching (SC crosstalk and SC no-crosstalk), divergent thinking task (flexibility DT and fluency DT), verbal fluency task (verbal fluency); Vocabulary knowledge task (VKT) and perseveration and learned irrelevance task (PE incompatible, PE compatible, LI incompatible, LI compatible).

TABLE 4.
Means, Standard Deviations, and Correlations with Confidence Intervals

Variable	M	SD	1	2	3	4	5	6	7	8	9
1. verbal fluency	18.09	3.86									
2. fluency DT	11.74	6.72	.39** [.22, .53]								
3. flexibility DT	4.26	1.67	.36** [.20, .51]	.75** [.66, .82]							
4. VKT	29.02	4.85	.37** [.20, .51]	.21* [.04, .38]	.25** [.07, .41]						
5. PE incompatible	-0.26	105.84	.03 [-.15, .21]	.16 [-.02, .33]	.17 [-.01, .34]	.26** [.08, .41]					
6. LI incompatible	-0.11	159.37	.11 [-.06, .29]	.04 [-.14, .22]	.08 [-.10, .26]	.08 [-.10, .26]	.29** [.12, .45]				
7. PE compatible	-39.38	121.48	.05 [-.13, .23]	.11 [-.07, .28]	.05 [-.13, .23]	.31** [.14, .46]	.58** [.45, .69]	.16 [-.01, .33]			
8. LI compatible	-46.47	112.21	.01 [-.16, .19]	.07 [-.11, .24]	-.03 [-.21, .15]	-.02 [-.19, .16]	-.08 [-.26, .10]	.19* [.01, .36]	.02 [-.16, .20]		
9. SC crosstalk	70.03	23.80	-.05 [-.22, .13]	.09 [-.09, .27]	.14 [-.03, .31]	.03 [-.15, .21]	.03 [-.15, .21]	.03 [-.15, .21]	.11 [-.07, .28]	-.13 [-.30, .05]	
10. SC no-crosstalk	42.47	11.86	-.04 [-.22, .14]	.11 [-.07, .28]	.15 [-.03, .32]	.04 [-.14, .22]	.02 [-.16, .20]	.07 [-.11, .24]	.12 [-.06, .29]	-.13 [-.30, .05]	.96** [.94, .97]

Note. Verbal fluency = verbal fluency task, Fluency DT and Flexibility DT = divergent thinking task, VKT = vocabulary knowledge test; PE incompatible, LI incompatible, PE compatible, and LI compatible = perseveration and learned irrelevance task; SC crosstalk and SC no-crosstalk = task-switching. Values in square brackets indicate 95% CIs for each correlation. The CI is a plausible range of population correlations that could have caused the sample correlation (Cumming, 2014).
*p <.05. ** p <.01.

the variables included in this study, namely, fluency DT, flexibility DT, verbal fluency, crystalized intelligence, and switch costs. The fluency DT and flexibility DT both entered into the same first cluster and correlated strongly. Although these two variables usually correlate, in the current study, this correlation was particularly strong (Silvia et. al., 2008), most likely due to the method of flexibility assessment used in the current version of the DT task. As described in the Methods section, we assessed flexibility DT on the basis of formal characteristics of the responses and not on semantic categories. Furthermore, in agreement with our expectations, the first cluster also included verbal fluency. Verbal fluency performance relies on psychomotor speed and executive processing represented by frequency of switching and inhibition (Amunts et al., 2020; Beilen et al., 2004; Oh et al., 2019). Several authors suggested modifications for the verbal fluency test, including the operationalization of an index of switching in order to clarify the contribution of CF to fluency performance (Oh et al., 2019).

Surprisingly, the first cluster included switch costs from the task-switching paradigm, which are defined as a pure measure of the time needed to change task sets: reallocate attention from one task-set to the other under limited time (Rogers et. al., 1998). In addition, crystalized verbal intelligence may also seem redundant or inappropriate in the first cluster. However, it should be remembered that the vocabulary knowledge test requires to quickly match the meaning of a reference word to one of four probes that belong to different semantic categories. This suggests that both switch costs and the vocabulary knowledge test rely on a dynamic switching between different tasks or categories requiring significant recruitment of the CF function. Accordingly, our unpublished study showed that the vocabulary knowledge test scores correlated with DT flexibility (Gruszka et. al. in prep.) .The discovery that switch costs, both fluencies, flexibility, and the vocabulary knowledge test scores cluster together suggests that similar processes were involved despite variations in the types of tasks and relations between them. Based on the literature reviewed above, we believe that all variables grouped in the first cluster rely on the efficiency of switching between categories of performance and psychomotor speed.

The second cluster consisted of four variables from the PE and LI task, meaning that switch costs and PE and LI indicators neither correlated nor grouped into a unique cluster, contrary to our expectations. At first glance, this observation is difficult to explain, because both tasks were designed to isolate specific, related aspects of shifting attention. The PE and LI paradigm (Dreisbach & Goschke, 2004) measures attentional shifting in a specific way. During the preshift stage of the test, participants learn to respond to stimuli of a particular colour, performing a letter categorization task or a digit categorization task, respectively. During the postshift stage, the change in relevant color occurs. At this point, participants are required to react to stimuli of a color different than the previous target stimulus (during the preshift stage). In the PE condition, the hitherto valid color is to be ignored, while in the LI condition, the previously ignored color now indicates the target stimulus. The attentional theory of discrimination learning (Mackintosh, 1975) posits that in this task, participants learn to attend to a stimulus (or a feature) that provides the best predictor of the presence of the rewarded (to be responded) stimulus. The former stimulus constitutes a conditioned stimulus, and the latter – an unconditioned stimulus. This process of attention allocation to the conditioned stimulus drives subsequent processing to the unconditioned stimulus. Allocation of attention is a basic process present in all types of discrimination learning. However, attentional shifts occur only when participants reallocate attention to another feature of the stimulus (e.g., from color to shape). Such reallocation is present in the extradimensional shifts as well as in task-switching. It is costly, increases error rates, and slows responding. Other forms of discrimination learning (e.g., intradimensional shifts or reversal shifting which are performed due to reward-contingency change) do not require reallocation of attention (Mackintosh, 1975; Nilsson et al., 2015). This means that according to attentional theory of discrimination learning (Mackintosh, 1975), the PE and LI task used in this study may not require attentional set-shifting, but it still requires the overcoming of prepotent responses. Thus, the second cluster represents a learning component of CF.

Based on the current study, we propose the following recommendations for CF assessment. First, for clinical needs, one could foresee a measure of CF modeled after the vocabulary knowledge test. This test has several advantages. It is a reasonably simple task, with a simple scoring method. Yet, it correlates well with other, more complicated CF measurement methods. It is possible to easily adjust the level of difficulty of the vocabulary knowledge test by manipulating its semantic content (e.g., using more or less common words).

Second, the task requirement of switching attention between different examples of the same dimension (e.g., from black to white) or between different dimensions or features of the same stimuli (e.g., from color to shape) is crucial. Theoretically, only switching between dimensions or features requires reallocation of attention and counts as an attentional shift (Mackintosh, 1973). Our study supports this supposition by showing that the task that relies upon switching between different examples of the same dimension measures only the effects of previous reward contingency on current task performance or the original conditioned-unconditioned stimulus association's stability. However, it does not correlate with typical CF measurements (divergent thinking, task switching) since they rely upon attentional set-shifting.

Our study has several limitations. In particular, we relied on correlations and cluster analysis using Ward's method, as the number of the participants did not allow for performing a factor analysis, which can potentially be seen as a better method to understand the relationships between different tasks to measure CF. The cluster analysis is an exploratory technique, and observed results depend heavily on the chosen method and statistical distance (Saraçli et al., 2013). On the other hand, Ward's method is considered much better than other cluster analyses (Blashfield, 1976). In comparison with other methods, it is considered accurate and it minimizes the variance between elements (Esztergár-Kiss & Caesar, 2017). Furthermore, the tasks were characterised by various levels of reliability. In the case of LI and PE indices, the reliability was quite low. Finally, several attempts were made to measure CF with self-reported questionnaires, such as the Cognitive Flexibility Scale (Martin & Rubin, 1995) and the Cognitive Flexibility Inventory (Dennis

& Vander Wal, 2010; Portoghese et al., 2020). However, the scales were developed in the clinical context to measure specific skills necessary to replace maladaptive thoughts with more balanced thinking. This specific application of CF is beyond the scope of the current study.

In summary, our results accord well with the observations of Eslinger and Grattan (1993), Boot et al. (2017) and Filippetti and Krumm (2020), suggesting that a single CF mechanism is insufficient to understand the heterogeneous nature of observations linking CF and its role in behavior and brain function. Our study adds to an existing body of work by confirming a two-factor structure of CF also in an adult population. It suggests two separate factors contributing to CF measurement: (a) speed of switching and (b) overcoming of the prepotent response.

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The committee for ethics in studies involving human participants, assigned by the Institute of Psychology, Jagiellonian University in Krakow, approved this study. According to the Helsinki Declaration, participants signed informed written consent forms.

The study was not preregistered.

DATA AVAILABILITY

Data for this study can be accessed at: https://ruj.uj.edu.pl/xmlui/handle/item/276979

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APPENDIX

TABLE A1.
An Overview of the Descriptive Data of Variables from the Tasks Used in the Current Project

	N	Mean	Median	SD	Minimum	Maximum	Skewness	SE	Kurtosis	SE
Fluency1	121	25.818	25	6.28	12	43	0.2809	0.220	−0.336	0.437
Fluency2	121	18.628	19	4.98	7	31	0.1279	0.220	−0.509	0.437
Fluency3	121	9.835	10	3.33	3	24	0.9216	0.220	2.159	0.437
Verbal fluency	121	18.094	18.00	3.86	10.0	28.0	0.3619	0.220	−0.319	0.437
Fluency_DT	121	11.934	10	6.95	2	37	1.0851	0.220	1.003	0.437
Flexibility_DT	121	4.264	4	1.67	1	8	−0.0893	0.220	−0.599	0.437
VKT	121	29.017	30	4.85	12	38	−0.6404	0.220	0.396	0.437
PE_incompatible_after_switch	121	810.744	774.63	180.67	411.8	1614.9	1.3107	0.220	3.435	0.437
PE_incompatible_before_switch	121	811.004	781.25	184.38	433.1	1399.6	0.8651	0.220	0.692	0.437
PE_incompatible	121	−0.261	6.23	105.84	−415.7	459.4	0.0916	0.220	4.194	0.437
LI_incompatible_after_switch	121	822.831	784.07	221.05	499.4	1915.0	2.4653	0.220	9.040	0.437
LI_incompatible_before_switch	121	822.944	786.87	201.69	468.6	1496.7	1.2359	0.220	1.664	0.437
LI_incompatible	121	−0.112	−3.00	159.37	−619.5	1068.9	1.7192	0.220	19.193	0.437
PE_compatible_after_switch	121	757.976	721.47	196.03	436.5	1849.8	2.1694	0.220	8.023	0.437
PE_compatible_before_switch	121	797.358	758.38	186.57	431.9	1607.2	1.1726	0.220	2.162	0.437
PE_compatible	121	−39.382	−36.02	121.48	−408.4	579.9	0.8215	0.220	6.347	0.437
LI_compatible_after_switch	121	767.923	738.87	193.60	432.4	1538.8	1.5455	0.220	3.094	0.437
LI_compatible_before_switch	121	814.391	786.13	204.85	453.5	1497.8	1.1236	0.220	1.350	0.437
LI_compatible	121	−46.468	−35.63	112.21	−374.3	443.1	0.2273	0.220	2.868	0.437
Switch_ cross	121	878.451	871.47	27.50	857.9	1039.3	3.4504	0.220	14.060	0.437
No-Switch_cross	121	808.423	808.29	17.82	687.1	881.8	−1.7033	0.220	20.138	0.437
SC_cross	121	70.028	61.97	23.80	55.6	202.4	3.4288	0.220	13.137	0.437
Switch_no-cross	121	625.890	625.18	13.44	610.7	727.4	5.0232	0.220	31.936	0.437
No-Switch_no-cross	121	583.422	585.98	8.58	557.9	621.3	-0.4195	0.220	3.355	0.437
SC_no-cross	121	42.468	38.63	11.86	35.9	107.4	3.8808	0.220	16.453	0.437

Note. verbal fluency task (Fluency1, Fluency2, Fluency3 and Verbal fluency), divergent thinking (Fluency_DT and Flexibility_DT), Vocabulary knowledge test (VKT), perseveration and learned irrelevance task (PE_incompatible_after_switch; PE_incompatible_before_switch, PE_incompatible, LI_incompatible_after_switch, LI_incompatible_before_switch, LI_incompatible, PE_compatible_after_switch, PE_compatible_before_switch, PE_compatible, LI_compatible_after_switch, LI_compatible_before_switch and LI_compatible) and task – switching (Switch_cross, No-Switch_cross, SC_cross, Switch_no-cross, No-Switch_no-cross and SC_no-cross). Abbreviations used in the table: LI – learned irrelevance, PE – perseveration, Fluency1 – fluency score for the first category, Fluency2 – fluency score for the second category, Fluency3 – fluency score for the third category, SC – switch costs.

The following formulas were used to calculate the indicators used in the analyses.
Fluency = (Fluency1+Fluency2+Fluency3)/3
SC crosstalk = Switch crosstalk – No-switch crosstalk
SC no-crosstalk = Switch no-crosstalk – No-switch no-crosstalk
PE compatible = PE compatible_after_switch – PE compatible_before_switch
LI compatible = LI compatible_after_switch – LI compatible_before_switch
PE incompatible = PE incompatible_after_switch – PE incompatible_before_switch
LI incompatible = LI incompatible_after_switch – LI incompatible_before_switch