Multidimensionality in Executive Function Profiles in Schizophrenia: A Computational
Approach Using the Wisconsin Card Sorting Task

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Abstract

Deficits in executive functions (EF) are frequently implicated in the aetiology of schizophrenia. However, no consensus exists regarding the contribution of EF to the dysfunctions observed in these individuals, with competing accounts arguing a primary role for deficits in inhibition, shifting and updating. We examine an alternative proposal referred to as *the multidimensional hypothesis* – rather than performance on cognitive tasks being primarily dependent on a single EF, that performance is multiply realised by a *range* of uneven EF profiles. We describe a computational approach, using the WCST, that allows manipulations to ability levels of processes relating to each EF component to be explicitly assessed. Our central objective is to determine whether models exhibiting unique profiles of EF abilities may simulate the performance of three target groups: individuals with schizophrenia, healthy first-degree relatives, and controls. For each target group, we show that of the performance measures yielded by the WCST, perseverative errors (PE; commonly assumed to rely heavily on EF) are simulated by multiple models. For a range of secondary measures (cards sorted, categories completed and non-perseverative errors; assumed less specific to EF abilities) our manipulations show little resemblance to the target groups. We view these results to support the multidimensional hypothesis, in that (1) no single EF process accounts for the poorer performance of the schizophrenic group, and (2) performance of PE in the target groups is achieved in models of diverse EF profiles. The implications of these findings for the study of EF in neuropsychological disorders are discussed.

Keywords: executive function, schizophrenia, endophenotype, Wisconsin card sorting task (WCST), perseveration errors, multidimensional

Background

Within the psychological literature there is broad agreement with the view that high-level cognitive behaviours (i.e., those requiring attention, strategy selection and problem solving) are mediated by a relatively small number of executive functions (EF), termed *updating*, *shifting* and *inhibition* (Miyake et al., 2000). The role proposed for each EF varies. For example, updating acts to monitor and manipulate the contents of working memory in order to ensure relevant information is available to facilitate task performance. Shifting concerns the disengagement of attention from one mental set and the subsequent engagement of another that is more appropriate to the task at hand. And, inhibition acts to suppress automatic responses that are irrelevant to successful task completion (Friedman & Miyake, 2017; Miyake et al., 2000). Given the central importance of EF to every-day cognitive functioning (Lezak et al., 2004), it is perhaps unsurprising that deficits in these processes have been frequently implicated in many cognitive and neuropsychological disorders (e.g., Stefanopoulou et al., 2009). In this paper, we focus on the neuropsychological disorder of schizophrenia – a disorder comprising of heterogeneous symptoms for which a number of competing accounts exist relating to the primary underlying cognitive deficit. We detail a computational methodology that is aimed at testing the notion that rather than the cognitive deficits in schizophrenia primarily involving a deficit within a single EF component, that these may instead be accounted for by multiple combinations of varying levels of EF abilities.

The relation of EF to schizophrenia

Schizophrenia is primarily characterised by hallucinations, delusions and disordered speech, but can also include disorganised behaviour such as lack of impulse control, as well as negative symptoms such as anhedonia (American Psychiatric Association, 2013). Whilst there is evidence of both genetic and neurological bases to the disorder (e.g., Hilker et al., 2018; Purcell et al., 2014), views concerning the causal role of these in schizophrenia is mixed (e.g., Frith, 2014; Gejman et al., 2011). Within the study of cognitive functioning associated with the disorder, research has showed that individuals with schizophrenia generally have markedly poorer problem-solving and decision-making abilities compared to healthy controls (Heerey et al., 2008; Morris et al., 1995). And, claims have been made that deficits in higher-order cognitive processes may be directly implicated in the aetiology schizophrenia (e.g., Beck & Rector, 2005; Frith, 2014; Stefanopoulou et al., 2009; Szöke et al., 2005). Further support for this view, and the

genetic bases of schizophrenia, comes from studies showing that compared to controls, healthy first-degree relatives of those with schizophrenia (HFR-SCZ) show deficits in tasks involving EF (Stefanopoulou et al., 2009; Szöke et al., 2005)

Though evidence appears to be growing of the role of EF in the disorder, isolating exactly which EF processes underlies the difficulties observed in schizophrenia has been challenging. For example, a range of studies have provided support for the notion that deficits in inhibition are primarily responsible for problems with impulse control (e.g., Kiehl et al., 2000). Conversely, one can find a range of evidence suggesting deficits in shifting are of key importance in explaining issues relating to attention (e.g., Gilleen et al., 2016). Still other research suggests issues related to poor memory are due to deficits in updating (e.g., Galletly et al., 2007). Identifying how EF components contribute to the dysfunction observed in schizophrenia is important to progressing our understanding of how the disorder emerges and is maintained, and may be crucial to the future optimisation of treatment and therapy programs.

Assessing executive functioning

The Wisconsin Card Sorting Task (WCST; Berg, 1948), is one of many tasks that have been developed to provide a measure of executive functioning. The task comprises four 'key cards' and a set of 64, or 128 cards each depicting geometric shapes that vary in their colour and number. The key cards remain fixed throughout trials. However, on each trial participants are required to take a card from the set and match it to one of the four key cards. Each card may therefore be matched according to number, colour, or shape. Initially, participants are unaware of the dimension they are required to match to. Instead, this is determined via trial-and-error and feedback provided by the experimenter (correct/incorrect). Once the correct matching strategy has been identified, participants repeat this strategy until, at a given point (usually after either six, or ten consecutive correct responses), the experimenter changes the dimension-to-match. Once again, the participant must determine what the new matching strategy is, and the process repeats for one of the other dimensions (colour, shape or number).

Performance on the WCST may be objectively measured in several ways. For instance, the number of correct cards sorted, the number of categories completed, and the number of perseveration as well as non-perseveration errors each allow for inferences to be made with respect to possible deficits in problem solving. Although studies vary in the metrics included for analysis, perseveration errors (PE) appears to be used most

consistently. PE refers to the number of times a participant continues to use a strategy that was previously correct, after receiving feedback that it is incorrect (Heaton, 1981). Importantly, within the literature on schizophrenia there is evidence suggesting PE is a robust endophenotype of the disorder (e.g., Jameson et al., 2011). For example, meta-analyses have shown that compared to controls, a greater number of PE are made by individuals with schizophrenia (mean effect $d=.84$), as well as their healthy first-degree relatives (mean effect $d=.26$; Stefanopoulou et al., 2009; Szoke et al., 2005), thus suggesting PE is related to heritable components of schizophrenia. Furthermore, studies have found that the number of perseveration errors made by individuals with schizophrenia is strongly associated with measures of the severity of the disorder (Koren et al., 1998). Thus, in conjunction or in isolation, metrics yielded from the WCST are potentially useful measures of EF because the task relies on each EF process for successful task completion. That is, efficient updating is required for participants to maintain in memory the current strategy, as well as previously used strategies. Similarly, important is the ability to inhibit strategies that were previously useful, but which are no longer correct. And, effective shifting is needed for participants to successfully focus attention on new candidate features when the dimension-to-match to changes.

The Current Study

Though the literature supports the view that deficits in EF play an important role in the problems observed in schizophrenia, research examining the relative contribution of each EF to deficits is lacking. In this paper, we adopt a computational approach with the aim of simulating the pattern of results demonstrated in the literature on the WCST by three target groups: (1) individuals with schizophrenia, (2) healthy first-degree relatives and (3) typically-developing controls. We then examine whether multiple combinations of ability levels of updating, shifting and inhibition give rise, in the first instance to the number of PE, and secondly to the number of cards sorted, categories completed, and number of non-perseveration errors that are typically found in our target groups. This approach, if successful, might help reconcile mixed findings within the literature concerning the role of EF in the disorder, and provide support for the *multidimensional hypothesis* – that overall cognitive performance is multiply realised by a range of uneven profiles of EF abilities.

The specific computational approach we use extends on the work of Fox and Das (2000). Fox and Das (2000) developed a framework demonstrating how component

cognitive processes contribute to decision-making in expert systems¹. Such computational approaches have proved valuable in exploring theorised mechanisms within a number of cognitive domains (e.g., Baughman & Cooper, 2007; Baughman & Thomas, 2008; Mareschal, 2006; Thomas et al., 2012; Thomas et al., 2009). The Fox and Das (2000) framework thus offers the potential to examine the effects of varying levels of ability in each EF on the overall number of PE made on the WCST. Before we set out the detail of these models, we first briefly describe the general problem-solving framework developed by Fox and Das (2000).

A Computational System of General Cognition

The Theory of Willed and Automatic Action (Norman & Shallice, 1986) is a general cognitive framework that attempts to explain human decision making. This theory proposes a two-system structure; the Contention Scheduling (CS) system that controls habitual behaviour, and the Supervisory Attentional System (SAS) that guides behaviour in novel situations. Glasspool (2005) showed this structure was highly similar to artificial intelligence expert systems such as the Fox and Das (2000) Domino Agent. Glasspool (2005) demonstrated that the Domino Agent could be combined with the Theory of Willed and Automatic Action to produce a system that could facilitate computational modelling (see Figure 1). Importantly, each of the three EF components can be mapped onto this integrated framework (see Method section for details), thus offering a platform to test the effect of altering levels of EF performance, and ultimately the multidimensional hypothesis – that multiple combinations of uneven EF abilities result in the same overall level of performance.

-----Insert Figure 1 here-----

Several computational models of the WCST exist. In many cases, the primary aim for these has been to develop a model that is biologically plausible, in order to assess the effects on performance of targeted ‘lesions’ to components modelling frontal and deep brain regions (see e.g., Amos, 2000; Caso & Cooper, 2017; Dehaene & Changeux, 1991; Gläscher et al., 2019; Kimberg & Farah, 1993; Leven & Levine, 1987; Levine & Prueitt, 1989; Rougier & O’Reilly, 2002). And, still other approaches have sought to develop mathematical models that are derived from the use of data from patients with neurological

¹ Expert systems are designed to consistently perform tasks without error.

disorders (e.g., Steinke, Lange, Seer, et al., 2018). In contrast, the approach we take involves the development of a range of models of the WCST that allow for a cognitive level of description of the consequences of changes to the processes underlying problem solving. Embedding these models within a cognitive framework, thus allows us to assess the precise effects of discrete manipulations to the individual EF components theorised to be important to performance on the WCST (Glasspool, 2005). Using an expert model, that is, one producing no PE on the WCST (developed by Cooper; 2002), our central objective was to develop a series of model variants, each exhibiting a unique EF profile by altering the levels of functioning of each EF process. Our overarching research questions are: to what extent might stepwise manipulations to the EF components within a computational model, result in performance on the WCST that simulates the performances typically observed in (a) individuals with schizophrenia (b) their healthy first-degree relatives, and (c) controls, in the number of perseveration errors (PE)? And secondly, to what extent might these manipulations also simulate the number of correct cards sorted, categories completed and non-perseveration errors typically observed within the target groups?

Method

Design

We used a between-groups design to compare the number of PE made on the WCST by models comprised of different EF profiles. The number of PE was thus the dependent variable, and the between-groups independent variable comprised a total of 48 distinct models, each exhibiting a unique combination of EF ability levels. Specifically, the 48 models were generated from implementing 4 levels of ability to inhibition and to updating (i.e., high/medium/poor/very poor) and 3 levels of ability in shifting (high/medium/poor)². See Table 1.

Participants

Inspections of normality using histograms revealed that each model variant required a minimum of 20 virtual participants to produce an approximately normal

² The process of shifting relied on ranking strategies, using whole numbers, based on the possible fit of each strategy at any given time. Therefore, manipulations to shifting comprised assigning values of '0', representing no shifting, '1' representing moderate shifting towards and '-1' away from a given strategy, values of '2' represented a strong shift towards, and '-2' a strong shift away from a strategy.

distribution of PE. Therefore, 20 virtual participants populated each of our 48 models, resulting in a total of 960 virtual participants.

To compare model data to our target groups (WCST performance of individuals with schizophrenia, healthy first-degree relatives, and controls) we reviewed published studies using WCST within these populations (see Online Resources for search and inclusion criteria as well as details of studies used).

Measures

We used the 128-card version of the WCST (Heaton, 1981), comprising two sets of 64 cards each showing a number (1, 2, 3, or 4) of coloured (green, red, yellow or blue) geometric shapes (crosses, circles, stars or triangles).

Procedure

COGENT (Cooper, 2002) is a hybrid symbolic-connectionist cognitive modelling platform based on the Prolog programming language that allows users to build models of a given system using *processes* (components within which rules can be specified regarding how information is manipulated), *buffers* (components used to store information within the system), and *compounds* (which can include sub-levels of processes and buffers). The Online Resources display these components within the Supervisory Attentional System modelled within COGENT (for a fuller description, see Cooper, 2002).

The Contention Scheduling (CS) compound contains sub-processes which represent activation levels related to three schemas, each representing one of the three task-relevant strategies (i.e., sort to colour, shape or number). Schemas within the CS are influenced by activity from the level above (i.e., within the SAS) via either inhibitory or excitatory signals that weaken or strengthen the likelihood of schemas being selected for action. Once a schema receives enough excitation to reach its threshold, a signal is sent to initiate the action related to the corresponding schema. The Online Resources depicts the relative levels of activation for each schema within the *Schema Hierarchy* for a presented card.

The *expert model*, developed within COGENT, served as the basis for the range of our models. Levels of Updating and Inhibition were altered to 20%, 33%, 66% and 99% (respectively representing *very poor*, *poor*, *medium* and *high*) of expert functioning, and Shifting was manipulated to 33%, 66% and 99% of the expert model's functioning level, resulting in a total of 48 model variants (i.e., 4x4x3), spanning all possible combinations of

the EF component abilities. Table 1 displays the implementation values of the three EF components.

Table 1.
Values Implemented within each EF process

EF Functioning Level	Updating	Shifting	Inhibition
<i>Very poor</i>	0.07	-	-0.10
<i>Poor</i>	0.12	0, 0	-0.22
<i>Medium</i>	0.24	1, -1	-0.44
<i>High</i>	0.37	2, -2	-0.65

Implementing and manipulating updating.

We instantiated deficits to Updating via changes to the *Fire Rate* property of the *Belief Update* process (see Online Resources for a illustration). Fire Rate controls the frequency with which rules fire, and the rules within *Belief Update* work to remove older strategy-based information and send new strategy-based information to *Working Memory*. Consistent with conceptual accounts (e.g., Miyake et al., 2000), the results of these manipulations had effects on both the removal of irrelevant information, and the addition of relevant information to working memory.

Implementing and manipulating shifting.

Shifting was manipulated via changes to a rule within the *Evaluation* process (see Online Resources). In the expert model, each possible strategy (i.e., to sort to colour, shape or number) is assigned a value depending on how well a strategy appears to fit a given scenario and given feedback (correct/incorrect). These weighted values therefore allow strategies to be evaluated within the model. Within the expert model, a value of 2 is used to weight the model’s preference towards a strategy whilst a value of -2 biases the model to shift away from a sorting strategy (see Online Resources for a illustration). By altering the values assigned to strategies within this rule we could thereby control the extent to which models exhibited efficient disengagement from a non-relevant mental set, and the active selection of more appropriate ones (Miyake et al., 2000).

Implementing and manipulating inhibition.

We manipulated the extent to which models could actively suppress previously useful strategies via changes to rules in *Inhibition*. Specifically, this process acts to send

negative activation to the *Schema Hierarchy* in response to accumulating evidence (via feedback) that the currently used sorting strategy is incorrect. Sending negative activation reduces the probability that a given strategy will be selected, and sending positive activation increases the likelihood of a strategy selection (see Online Resources for a depiction). By manipulating the levels of activation sent to Schema Hierarchy, we thus could affect the persistent use of incorrect strategies, and more effortful selection of new ones (Miyake et al., 2000).

Results

Perseveration Errors

Table 2 displays the mean number of PE for each of the target groups that we aim to simulate in our models. Effect sizes were calculated to provide estimates of the magnitude of difference in average PE between the three populations. As Table 2 shows, healthy first-degree relatives (HFR-SCZ) typically perform more PE than Controls on the WCST, with this effect size being small to moderate ($d = .43$), and individuals with schizophrenia (SCZ) typically perform more PE than Controls ($d = 2.19$), and HFR-SCZ ($d = 1.42$), with both of these effect sizes being large (Cohen, 1992).

Table 2.
Mean Number of Perseveration Errors Made on the WCST by Target Groups

Population	<i>N</i>	Mean Age (<i>SD</i>)	Mean PE (<i>SD</i>)	95% CI
<i>Controls</i>	1482	34.55 (9.34)	11.13 (4.68)	[8.66, 13.61]
<i>HFR-SCZ</i>	1891	37.33 (9.04)	13.82 (7.91)	[10.37, 17.28]
<i>SCZ</i>	1813	32.36 (7.63)	25.26 (8.19)	[19.78, 30.74]

Note. *N* = Total Sample Size. *SD* = Standard Deviation. PE = Perseveration Errors. 95% CI = 95% Confidence Interval. *HFR-SCZ* = Healthy First-degree Relatives of People with Schizophrenia. *SCZ* = People with Schizophrenia.

In Figure 2 we present the main results of our simulations, overlaid with 95% CI for each of our target groups (derived from Table 2). Notably, Figure 2 shows a great deal of variability in the mean number of errors made by the models (lowest mean PE = 1.15, highest mean PE = 41.70). Furthermore, one can see that some of the model variants made fewer PE than the number expected for controls, and that the poorest functioning model (model 1) made a greater number of PE than that expected of individuals with schizophrenia. This range of performance in our models, indicates that our approach is sensitive to examining the basis of deficits produced by each of our target groups.

With regard to the central question, of the extent to which deficits to single versus multiple components of EF may underlie performance on the WCST, Figure 2 shows that no one single model simulated levels of PE for any of the target groups. Rather, the results

show that a number of model variants, each comprised of different EF profiles, were capable of simulating the range of performance for each group. Results show a substantial degree of overlap with 15 models falling within the range of more than one target group. For instance, of the 48 models that we tested, a total of 20 models fell within the range of PE made by Controls, 16 models within the range of HFR-SCZ and 13 models fell within the range of SCZ. Figure 2 also shows that of the total 48 models, 15 model variants produced mean levels of PE outside of the range of any target group (14 of these models were at levels below that normal of the Control group, and 1 model exhibited a mean PE above that expected for the SCZ group).

----- Insert Figure 2 here-----

Table 3 shows the composition of each model variant (i.e., levels of shifting, updating, and inhibition) and the mean number of PE (with 95% confidence intervals) generated via manipulations to the processes relating to EF abilities. As expected, the best functioning model (model 48) comprised highest levels of abilities in each EF component (mean PE=1.15), and the poorest functioning model (model 1) comprised lowest levels of abilities in each EF component (mean PE=41.70). Table 3 also indicates the target group that performance of each model fits with.

Table 3.

Performance on the WCST by models with unique EF profiles

Model Number	Model Variant (Updating/Shifting/Inhibition)	Mean PE	SD of PE	95%CI	Group Simulated
1	Poor+/Poor/Poor+	41.70	11.07	[36.52, 46.88]	+S
2	Poor/Poor/Poor+	25.85	3.98	[23.99, 27.71]	S
3	Medium/Poor/Poor+	25.60	4.68	[23.41, 27.79]	S
4	High/Poor/Poor+	27.55	6.20	[24.64, 30.45]	S
5	Poor+/Medium/Poor+	22.90	3.06	[21.47, 24.33]	S
6	Poor+/Medium/Poor	14.20	3.47	[12.57, 15.83]	C,H
7	Poor+/Medium/Medium	8.85	2.87	[8.06, 9.64]	C
8	Poor+/Medium/High	8.00	4.45	[6.02, 9.97]	C
9	Poor+/High/Poor+	24.95	2.72	[23.68, 26.22]	S
10	Poor+/High/Poor	14.30	2.94	[12.92, 15.68]	C,H
11	Poor+/High/Medium	9.45	1.64	[8.68, 10.22]	C
12	Poor+/High/High	6.70	2.60	[5.48, 7.92]	-C
13	Poor+/Poor/Poor	20.00	7.70	[16.58, 23.46]	H,S
14	Poor+/Poor/Medium	12.85	4.38	[10.80, 14.90]	C,H
15	Poor+/Poor/High	11.00	3.96	[9.15, 12.85]	C,H
16	Poor/Medium/Poor+	23.20	3.98	[21.34, 25.06]	S
17	Medium/Medium/Poor+	21.85	2.89	[21.85, 23.20]	S
18	High/Medium/Poor+	20.19	3.36	[18.66, 21.71]	S
19	Poor/High/Poor+	22.85	3.45	[21.23, 24.47]	S
20	Medium/High/Poor+	21.45	2.96	[20.06, 22.39]	S
21	High/High/Poor+	21.50	3.12	[20.04, 22.96]	S
22	Poor/Poor/Poor	18.35	6.44	[15.33, 21.37]	H,S
23	Poor/Poor/Medium	11.40	4.73	[9.19, 13.61]	C,H
24	Poor/Poor/High	10.90	7.03	[7.61, 14.19]	C,H
25	Poor/Medium/Poor	11.55	2.68	[10.29, 12.81]	C,H
26	Poor/Medium/Medium	7.10	1.37	[6.45, 7.74]	-C
27	Poor/Medium/High	4.60	1.93	[3.70, 5.50]	-C
28	Poor/High/Poor	11.85	2.30	[10.77, 12.83]	C,H
29	Poor/High/Medium	7.50	1.57	[6.76, 8.24]	-C
30	Poor/High/High	4.35	1.69	[3.56, 5.14]	-C
31	Medium/Poor/Poor	13.65	4.70	[11.45, 15.85]	C,H
32	Medium/Poor/Medium	12.45	6.65	[9.34, 15.56]	C,H
33	Medium/Poor/High	6.05	3.94	[4.21, 7.89]	-C
34	Medium/Medium/Poor	9.50	2.01	[8.56, 10.44]	C
35	Medium/Medium/Medium	6.70	1.17	[6.15, 7.25]	-C
36	Medium/Medium/High	2.00	1.21	[1.43, 2.56]	-C
37	Medium/High/Poor	9.80	1.51	[9.09, 10.51]	C
38	Medium/High/Medium	6.65	1.23	[6.08, 7.22]	-C
39	Medium/High/High	2.19	1.00	[1.58, 2.52]	-C
40	High/Poor/Poor	14.6	5.03	[12.25, 16.95]	C,H
41	High/Poor/Medium	9.75	6.59	[6.66, 12.83]	C,H
42	High/Poor/High	9.90	6.92	[6.66, 13.14]	C,H
43	High/Medium/Poor	14.85	4.45	[12.77, 16.93]	C,H
44	High/Medium/Medium	7.25	1.52	[6.54, 7.96]	-C
45	High/Medium/High	4.75	1.71	[3.95, 5.55]	-C
46	High/High/Poor	8.50	1.43	[7.82, 9.17]	C
47	High/High/Medium	6.65	1.27	[6.06, 7.24]	-C
48	High/High/High	1.15	0.88	[0.74, 1.56]	-C

Note. Group Simulated shows the fit of each model to corresponding target group (C=Control, H=HFR-SCZ, S=Schizophrenia), +/- denotes performance levels above or under boundary ranges. PE = Perseveration Errors. SD = Standard Deviation. 95%CI = 95% Confidence Interval.

Returning to the question of multidimensionality, Table 3 shows that a number of model variants generated highly similar mean levels of PE. For instance, models 12, 38, and 47, each produced mean levels of PE between 6.65 and 6.70. Yet, no single EF component appears to be a necessary condition in determining this outcome. That is, whilst model 12 suggests that the effect of very poor levels of updating is compensated for by high levels of shifting and inhibition, low levels of updating are not critical to determining the level of PE. For example, model 47, which produced just .05 less PE, is comprised of high levels of updating, as well as high levels of shifting and medium inhibition.

Models 23, 25 and 28 also produced mean levels of PE that were very close to one another in range (11.40 – 11.85). As Table 3 shows, in each instance these models comprise poor levels of Updating, and that they each simulate levels of PE that fall within the ranges of Controls and HFR-SCZ. However, again, poor levels of updating do not exclusively determine levels of PE in these target groups. Models 31, 32, 34, 40 and 43 each also produce levels of PE within those target group ranges, but none of these comprise poor or very poor levels of updating.

Looking next to the model variants that fell within the range of individuals with schizophrenia (i.e., models 2-5, 9, 13 and 16-21), Table 3 shows that either poor or very poor inhibition is a composite feature for all these models. However, once again poor levels of inhibition do not determine levels of PE within the SCZ range. For example, a number of other models, each also comprising poor levels of inhibition, performed more accurately and were in ranges matching Controls or HFR-SCZ (see models 6, 10, 25, 28, 31, 34, 36, 40, and 43).

Taken together, and within the context of the target groups we have focused on, the current findings indicate that rather than performance on the WCST relying on any single EF component, that instead this may be determined equally by multiple EF profiles – each profile comprising various different EF strengths and weaknesses.

Exploratory analyses in the form of three, one-way ANOVA's were completed to compare the PE performed by the various levels of functioning within each EF component. The PE performed differed significantly between levels of EF functioning; updating, $F(3, 956) = 13.21, p > .001, \eta^2 = .04$; shifting, $F(2, 956) = 44.02, p > .001, \eta^2 = .08$; and inhibition, $F(2, 956) = 560.06, p > .001, \eta^2 = 0.64$. Descriptive statistics for the models at each level of updating, shifting and inhibition can be seen in Table 4.

Table 4.

Descriptive Statistics of Models' Performance at Each Level of Updating, Shifting and Inhibition

EF Component	Level of Functioning	Mean PE	SD of PE	95% CI
<i>Updating</i>				
	Poor+ (<i>n</i> = 240)	16.24	10.70	[14.88, 17.60]
	Poor (<i>n</i> = 240)	13.29	8.11	[12.26, 14.32]
	Medium (<i>n</i> = 240)	11.48	8.17	[10.43, 12.52]
	High (<i>n</i> = 240)	12.21	8.43	[11.14, 13.28]
<i>Shifting</i>				
	Poor (<i>n</i> = 320)	17.03	11.28	[15.78, 18.27]
	Medium (<i>n</i> = 320)	11.67	7.24	[10.88, 12.47]
	High (<i>n</i> = 320)	11.07	7.44	[10.25, 13.84]
<i>Inhibition</i>				
	Poor+ (<i>n</i> = 240)	24.86	8.25	[23.81, 25.91]
	Poor (<i>n</i> = 240)	13.44	5.02	[12.80, 14.08]
	Medium (<i>n</i> = 240)	8.72	3.89	[8.22, 9.21]
	High (<i>n</i> = 240)	5.04	5.04	[5.37, 13.84]

Note. EF = Executive Functioning. PE = Perseveration Errors. *SD* = Standard Deviation. 95% CI = 95% Confidence Interval, *n* = Group Sample Size.

Table 5 displays the results of pairwise comparisons following the three one-way ANOVAs. This table shows that very poor updating models performed significantly more PE than the poor, medium and high updating models. While, poor and medium, and poor and high updating models were not reliably different in the number of PE. Poor shifting models performed significantly more PE than medium and high shifting models. While, medium and high shifting models did not differ reliably in PE. Lastly, each inhibition model was reliably different in the number of PE, with very poor inhibition models performing the most PE and high inhibition models performing the least. Inspection of effect sizes across the EF components demonstrates further that changes to the models' inhibition ability had the greatest impact on the number of PE the models performed.

Table 5.

Within Component Functioning Comparisons

EF Component	Level of Functioning		Mean Difference	Std. Error	95%CI	<i>p</i>	<i>t</i>	<i>d</i>	
<i>Updating</i>									
<i>Shifting</i>	Poor+	Poor	2.95	.81	[0.79, 5.10]	.002	3.62	0.24	
		Medium	4.76	.81	[2.61, 6.9]	<.001	5.84	0.38	
		High	4.03	.81	[1.88, 6.18]	<.001	4.95	0.32	
	Poor	Medium	2.81	.81	[-0.34, 3.97]	.158	2.23	0.14	
		High	1.08	.81	[-1.07, 3.24]	1.00	1.33	0.09	
	Medium	High	-0.73	.81	[-2.88, 1.42]	1.00	-0.90	-.006	
	Poor	Medium	5.37	.69	[3.72, 7.02]	<.001	7.80	0.50	
		High	5.79	.69	[4.14, 7.44]	<.001	8.41	0.04	
	Medium	High	0.43	.69	[-1.23, 2.08]	1.00	0.62	0.04	
	<i>Inhibition</i>								
	Poor+	Poor	11.46	.50	[10.14, 12.78]	<.001	22.90	1.48	
		Medium	16.07	.50	[14.75, 17.39]	<.001	32.11	2.08	
High		19.07	.50	[17.75, 20.39]	<.001	38.11	2.46		
Poor	Medium	4.61	.50	[3.29, 5.94]	<.001	9.22	0.60		
	High	7.61	.50	[6.29, 8.94]	<.001	15.22	0.98		
Medium	High	3.00	.50	[1.68, 4.32]	<.001	5.99	0.39		

Note. EF = Executive Functioning. Std. = Standard. 95%CI = 95% Confidence Interval. *p* = Probability. *t* = *t*-statistic. *d* = Cohens' *d*. Bonferroni adjusted for multiple comparisons

Figure 3 displays the mean PE (Y axis) performed by the 48 models at each level of functioning (X axis) of the three EF components. As expected, these results show a trend of declining PE (i.e., increasing accuracy on the task) when moving between the very poor to poor, poor to medium, and medium to high functioning levels of shifting and inhibition components. That is, as the ability levels of these processes increased, the lower the number of PE and the higher the accuracy on the task. However, counter to this, Figure 3 shows altering levels of updating had a different effect. For this process, models with a medium updating ability performed the lowest number of PE, while PE did not differ reliably in the poor versus high, or the medium versus high updating models.

-----Insert Figure 3 here-----

Secondary Outcome Metrics

Table 6 displays the mean number performance of Card Sorts, Categories Completed, and Non-Perseveration Errors for each of the target groups. At least one study reported each WCST outcome for each population of interest. As Table 6 shows, Controls typically performed more correct sorts than HFR-SCZ ($d = 1.24$) and people with schizophrenia ($d = .98$), with these effects being large. HFR-SCZ typically performed slightly more correct sorts than individuals with schizophrenia ($d = .14$), with this being a small effect (Cohen, 1992).

Controls also completed more categories on the WCST when compared to HFR-SCZ ($d = .23$), and people with schizophrenia ($d = 1.12$), with the former effect being small-to-medium and the latter being large. HFR-SCZ also typically completed more categories when compared to individuals with schizophrenia ($d = .80$) with the effect being large (Cohen, 1992).

People with schizophrenia typically performed more non-perseveration errors on the WCST than Controls ($d = .69$), and HFR-SCZ ($d = .58$) with the effect sizes both medium-to-large. Lastly, HFR-SCZ performed marginally more non-perseveration errors than Controls ($d = .07$) with the effect being small.

Table 6.

Mean Performance on Secondary Outcomes of the Target Groups on the WCST

Criteria	Controls (SD) [95%CI]	N	Mean Age (SD)	HFR-SCZ (SD) [95%CI]	N	Mean Age (SD)	SCHZ (SD) [95%CI]	N	Mean Age (SD)
Mean Correct Sorts	61.48 (7.56) [59.11, 63.85]	114	29.23 (6.20)	53.60 (4.90) [51.72, 55.48]	26	23.90 (1.60)	52.40 (10.76) [49.09, 55.71]	115	29.97 (6.07)
Mean Categories Completed	5.23 (1.24) [4.81, 5.66]	959	34.68 (9.90)	4.89 (1.67) [4.36, 5.43]	1759	36.51 (9.27)	3.47 (1.88) [2.87, 4.07]	1698	32.80 (7.86)
Mean NPE	11.47 (9.03) [8.27, 15.87]	441	30.09 (8.27)	12.16 (11.79) [9.59, 15.51]	1355	34.41 (7.55)	19.88 (14.69) [16.21, 23.55]	1449	30.23 (7.83)

Note. HFR-SCZ = healthy first-degree relatives of those with schizophrenia. *N* = sample size. 95%CI = 95% confidence interval. SD = standard deviation. NPE = non-perseveration errors.

Three one-way ANVOAs were completed to assess the effect of differing ability levels of each EF component on the number of correct sorts, categories completed, and non-perseveration errors the models performed. Overall, these results show that our manipulations to the models' EF abilities had little effect on secondary outcome measures. That is, altering the levels of updating ($F(3, 956) = .998, p = .398, \eta^2 = .003$), shifting ($F(3, 956) = .981, p = .375, \eta^2 = .002$), $F(3, 956) = .998, p = .398, \eta^2 = .003$), and inhibition ($F(3, 956) = .988, p = .998, \eta^2 = .003$) did not influence the number of correct card sorts within our models. Different ability levels of updating ($F(3, 956) = 2.01, p = .111, \eta^2 = .007$), shifting ($F(3, 956) = 2.01, p = .135, \eta^2 = .004$), and inhibition ($F(3, 956) = 2.001, p = .111, \eta^2 = .007$) yielded no differences in the number of categories completed. Finally, varying levels of updating $F(3, 956) = .411, p = .745, \eta^2 = .001$), shifting ($F(3, 956) = .850, p = .428, \eta^2 = .002$), and inhibition ($F(3, 956) = 1.56, p = .197, \eta^2 = .005$) also failed to affect the number of non-perseveration errors the models made. Table 7 displays the mean performance across all 48 models on the secondary WCST outcome measures.

Table 7.

Models Performance on Secondary Outcomes on the WCST

	Correct Sorts	Categories Completed	NPE
Mean	59.94	5.99	7.48
Performance			
<i>SD</i>	1.74	.046	1.13
95%CI	[59.83, 60.05]	[5.99, 6.00]	[7.41, 7.55]
Range	59.00 – 60.00	5.90 – 6.00	6.90 – 8.00

Note. Range refers to the mean performance of the lowest and uppermost scoring models at each criteria. NPE = non-perseveration errors, *SD* = standard deviation, 95%CI = 95% confidence interval.

Discussion

There is growing interest in understanding the role of specific cognitive processes in various neuropsychological disorders. However, to date, much research into the possible cognitive mechanisms underlying disorders like schizophrenia has attempted to isolate single cognitive processes that appear to be of crucial importance. Such unidimensional approaches have yielded little in the way of consensus and competing accounts can be found to separately argue for a central role of inhibition, shifting and updating. The objective within this study was to examine an alternative proposal we term the multidimensional hypothesis – rather than positing deficits to a single EF process as responsible for problems in reasoning and planning, that instead a broader mix of EF ability profiles may be equivalent in affecting performance on neuropsychological tasks. Using a computational model of the WCST, we manipulated the parameters of a base model to produce 48 models, each exhibiting a unique profile of abilities in EF processes related to shifting, updating and inhibition. Our results showed that a number of models were equivalent in simulating the performance of PE on the WCST for each of the target groups. Specifically, a total of 13 models simulated the number of errors typically made by individuals with schizophrenia, 16 models simulated the performance of the healthy first-degree relatives of those with schizophrenia, and 20 models simulated the number of errors typically made by typically developing adults. In addition to these, a further 15 models yielded PE performance ranges outside of any of our target groups. This range of variability is impressive considering that our manipulations were constrained to such a limited range of ability levels. Crucially though, and in relation to the question of multidimensionality, our results show that within each target group no single EF process was critical to overall performance on the task. That is, no particular deficit or level of EF ability was found to determine performance on the WCST. Rather, overall levels of performance were subserved by multiple, diverse profiles of abilities in all three EF components. These findings stand in contrast, and offers the possibility of reconciling claims that a single EF component is integral to performance on the WCST (e.g., Barceló & Knight, 2002; Hartman et al., 2001; Manoach et al., 2002).

In examining the EF profiles of models and their relation to levels of PE, we have shown that changes to levels of inhibition resulted in the greatest impact on WCST performance. Our findings extend upon current literature suggesting an important role of inhibition in the aetiology of schizophrenia. For example, Myles et al. (2017) found a descending pattern of inhibition ability between controls, HFR-SCZ and people with

schizophrenia. This is the same pattern of performance of PE we find between these populations on the WCST (Stefanopoulou et al., 2009). Furthermore, Nishimura et al. (2011) found poor inhibition ability to be related to the severity of various symptoms of schizophrenia, such as agitation and impulse control. Therefore, our findings are consistent with the view that inhibition has an inherent association with the disorder. However, as our results show, the interactions of all three EF components were still of utmost importance in determining the number of PE performed.

With regard to the secondary outcome measures, our results show that with the exception of one measure (cards sorted) in Controls, that varying levels of EF ability had little effect on cards sorted, categories completed and non-perseveration errors. This result is however consistent with previous research arguing that cognitive processes other than updating, shifting and inhibition, for example contextual reasoning, may be primarily responsible for the performance of correct card sorts, categories completed and non-perseveration errors on the WCST (e.g., Kaplan et al., 2006; Mizuno, 1991; Somsen, 2007; Stratta et al., 2000; Stuss et al., 2000).

Limitations and Directions for Future Research

Although we generated a number of unique models, the range of abilities that we instantiated within each of the EF processes were very limited. We used only 4 ability levels within updating and inhibition (very poor, poor, medium and high), and 3 levels within shifting (poor, medium and high) to produce a total of 48 combinations. Hence, one limitation of our study concerns the narrow range of abilities that we tested. In order to more fully evaluate the effect of finer-grained interactions between EF processes, future work might seek to sample abilities, for each EF process, from a greater range of normally distributed scores.

A second limitation of our approach concerns the fact that in our study we focused only on exploring the interactions between EF processes in stable, or fully developed models. Whilst each of the EF combinations that we produced could therefore be considered to represent ‘adult’ models, the approach we took does not provide us with a way of examining how ability on the task may be influenced by interactions of EF processes over development. This is a potentially important point as research has showed that profiles of relative strengths and weaknesses in EF abilities may change markedly over the course of development (Ramsden et al., 2011). Addressing these limitations may

prove particularly important to understanding the developmental time course of EF deficits within disorders such as schizophrenia.

Finally, our results revealed that the approach we took was unsuccessful in simulating the performance of our target groups on a number of secondary measures (i.e., correct cards sorted, categories completed, and non-perseveration errors). Although previous research has suggested that performance relating to these metrics are influenced more by processes not specifically targeted within our approach, a fuller model of performance on the WCST should ideally be capable of simulating these data also. Thus, we plan to extend the framework developed within COGENT, to explore the extent to which similar mixtures of underlying abilities in these processes may give rise to the broader patterns of performance.

Implications and Conclusions

The results presented here offer preliminary support for the multidimensional hypothesis. Rather than finding evidence of a single process underlying the performances of our target groups, we found that models exhibiting diverse, uneven profiles of EF abilities were equivalent in simulating performance on the WCST for each of our target groups. Thus, notwithstanding the limitations described above, the key implication of these results is the possibility that many of the mixed findings reported in the literature, concerning the basis of deficits in reasoning, problem solving and planning in neuropsychological disorders, may be reconciled under a multidimensional account.

References

- American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). American Psychiatric Association.
- Amos A (2000), A computational model of information processing in the frontal cortex and basal ganglia. *Journal of Cognitive Neuroscience*, 12(3), 505-519.
- Barceló, F., & Knight, R. T. (2002). Both random and perseverative errors underlie WCST deficits in prefrontal patients. *Neuropsychologia*, 40(3), 349-356.
- Baughman, F. D., & Cooper, R. P. (2007). Inhibition and young children's performance on the Tower of London task. *Cognitive Systems Research*, 8(3), 216-226.
- Baughman, F. D., & Thomas, M. S. C. (2008). *Specific impairments in cognitive development: A dynamical systems approach. Proceedings of the 30th Annual Meeting of the Cognitive Science Society* (pp. 23-26). Washington, U.S.
- Beck, A. T., & Rector, N. A. (2005). Cognitive approaches to schizophrenia: Theory and therapy. *Annu. Rev. Clin. Psychol.*, 1, 577-606.
- Berg, E. A. (1948). A simple objective technique for measuring flexibility in thinking. *The Journal Of General Psychology*, 39(1), 15-22.
- Caso, A., & Cooper, R. P. (2017). A Model of Cognitive Control in the Wisconsin Card Sorting Test: Integrating Schema Theory and Basal Ganglia Function. *Proceedings of the 39th Annual Meeting of the Cognitive Science Society* (pp. 210-215). London, U.K.
- Cohen, J. (1992). A power primer. *Psychological Bulletin*, 112(1), 155.

Cooper, R. P. (2002). *Modelling high-level cognitive processes*. Psychology Press.

Dehaene, S., & Changeux, J. P. (1991). The Wisconsin Card Sorting Test: Theoretical analysis and modeling in a neuronal network. *Cerebral Cortex*, 1(1), 62-79.

Fox, J., & Das, S. (2000). Safe and sound. *Artificial intelligence in hazardous applications*. AAAI Press.

Friedman, N. P., & Miyake, A. (2017). Unity and diversity of executive functions: Individual differences as a window on cognitive structure. *Cortex*, 86, 186-204.

Frith, C. D. (2014). *The cognitive neuropsychology of schizophrenia*. Psychology Press.

Galletly, C. A., MacFarlane, A. C., & Clark, C. R. (2007). Impaired updating of working memory in schizophrenia. *International Journal of Psychophysiology*, 63(3), 265-274.

Gejman, P. V., Sanders, A. R., & Kendler, K. S. (2011). Genetics of schizophrenia: new findings and challenges. *Annual Review Of Genomics And Human Genetics*, 12, 121-144.

Gilleen, J., David, A., & Greenwood, K. (2016). Self-reflection and set-shifting mediate awareness in cognitively preserved schizophrenia patients. *Cognitive Neuropsychiatry*, 21(3), 185-196.

Gläscher, J., Adolphs, R., & Tranel, D. (2019). Model-based lesion mapping of cognitive control using the Wisconsin Card Sorting Test. *Nature Communications*, 10(1), 1-12.

- Glasspool, D. W. (2005). The integration and control of behaviour: Insights from neuroscience and AI. In *Visions of mind: Architectures for cognition and affect* (pp. 176-203). IGI Global.
- Hartman, M., Bolton, E., & Fehnel, S. E. (2001). Accounting for age differences on the Wisconsin Card Sorting Test: Decreased working memory, not inflexibility. *Psychology and Aging, 16*(3), 385.
- Heerey, E. A., Bell-Warren, K. R., & Gold, J. M. (2008). Decision-making impairments in the context of intact reward sensitivity in schizophrenia. *Biological Psychiatry, 64*(1), 62-69.
- Hilker, R., Helenius, D., Fagerlund, B., Skytthe, A., Christensen, K., Werge, T. M., Nordentoft, M., & Glenthøj, B. (2018). Heritability of schizophrenia and schizophrenia spectrum based on the nationwide Danish twin register. *Biological Psychiatry, 83*(6), 492-498.
- Jameson, K. G., Nasrallah, H. A., Northern, T. G., & Welge, J. A. (2011). Executive function impairment in first-degree relatives of persons with schizophrenia: a meta-analysis of controlled studies. *Asian Journal of Psychiatry, 4*(2), 96-99.
- Kaplan, G. B., Şengör, N. S., Gürvit, H., Genç, İ., & Güzeliş, C. (2006). A composite neural network model for perseveration and distractibility in the Wisconsin card sorting test. *Neural Networks, 19*(4), 375-387.
- Kiehl, K. A., Smith, A. M., Hare, R. D., & Liddle, P. F. (2000). An event-related potential investigation of response inhibition in schizophrenia and psychopathy. *Biological Psychiatry, 48*(3), 210-221.
- Koren, D., Seidman, L. J., Harrison, R. H., Lyons, M. J., Kremem, W. S., Caplan, B., Goldstein, J. M., Faraone, S. V., & Tsuang, M. T. (1998). Factor structure of the

Wisconsin Card Sorting Test: Dimensions of deficit in schizophrenia.

Neuropsychology, 12(2), 289.

Lezak, M. D., Howieson, D. B., Loring, D. W., & Fischer, J. S. (2004).

Neuropsychological Assessment. Oxford University Press.

Manoach, D. S., Lindgren, K. A., Cherkasova, M. V., Goff, D. C., Halpern, E. F.,

Intriligator, J., & Barton, J. J. S. (2002). Schizophrenic subjects show deficient inhibition but intact task switching on saccadic tasks. *Biological Psychiatry*, 51(10), 816-826.

Mareschal, D. (2006). How computational models help explain the origins of reasoning.

IEEE Computational Intelligence Magazine, 1(3), 32-40.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D.

(2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology*, 41(1), 49-100.

Mizuno, M. (1991). Neuropsychological characteristics of right hemisphere damage:

investigation by attention tests, concept formation and change test, and self-evaluation task. *The Keio Journal of Medicine*, 40(4), 221-234.

Morris, R. G., Rushe, T., Woodruffe, P. W. R., & Murray, R. M. (1995). Problem solving

in schizophrenia: a specific deficit in planning ability. *Schizophrenia Research*, 14(3), 235-246.

Myles, J. B., Rossell, S. L., Phillipou, A., Thomas, E., & Gurvich, C. (2017). Insights to

the schizophrenia continuum: A systematic review of saccadic eye movements in schizotypy and biological relatives of schizophrenia patients. *Neuroscience & Biobehavioral Reviews*, 72, 278-300.

- 1 Nishimura, Y., Takizawa, R., Muroi, M., Marumo, K., Kinou, M., & Kasai, K. (2011).
2 Prefrontal cortex activity during response inhibition associated with excitement
3 symptoms in schizophrenia. *Brain Research*, 1370, 194-203.
4
5
6
7
8
9
10 Norman, D. A., & Shallice, T. (1986). Attention to action. In *Consciousness and self-*
11 *regulation* (pp. 1-18). Springer.
12
13
14
15
16 Purcell, S. M., Moran, J. L., Fromer, M., Ruderfer, D., Solovieff, N., Roussos, P.,
17 O'dushlaine, C., Chambert, K., Bergen, S. E., & Kähler, A. (2014). A polygenic
18 burden of rare disruptive mutations in schizophrenia. *Nature*, 506(7487), 185-190.
19
20
21
22
23
24 Ramsden, S., Richardson, F. M., Josse, G., Thomas, M. S. C., Ellis, C., Shakeshaft, C.,
25 Seghier, M. L., & Price, C. J. (2011). Verbal and non-verbal intelligence changes in
26 the teenage brain. *Nature*, 479(7371), 113-116.
27
28
29
30
31
32
33 Rougier, N. P., & O'Reilly, R. C. (2002). Learning representations in a gated prefrontal
34 cortex model of dynamic task switching. *Cognitive Science*, 26(4), 503-520.
35
36
37
38
39 Somsen, R. J. M. (2007). The development of attention regulation in the Wisconsin Card
40 Sorting Task. *Developmental Science*, 10(5), 664-680.
41
42
43
44
45 Stefanopoulou, E., Manoharan, A., Landau, S., Geddes, J. R., Goodwin, G. U. Y., &
46 Frangou, S. (2009). Cognitive functioning in patients with affective disorders and
47 schizophrenia: a meta-analysis. *International Review of Psychiatry*, 21(4), 336-356.
48
49
50
51
52
53 Steinke, A., Lange, F., Seer, C., & Kopp, B. (2018). Toward a computational cognitive
54 neuropsychology of Wisconsin card sorts: A showcase study in Parkinson's
55 disease. *Computational Brain & Behavior*, 1(2), 137-150.
56
57
58
59
60
61
62
63
64
65

1 Stratta, P., Daneluzzo, E., Bustini, M., Prosperini, P., & Rossi, A. (2000). Processing of
2 context information in schizophrenia: relation to clinical symptoms and WCST
3 performance. *Schizophrenia Research*, 44(1), 57-67.
4
5
6

7
8 Stuss, D. T., Levine, B., Alexander, M. P., Hong, J., Palumbo, C., Hamer, L., Murphy, K.
9 J., & Izukawa, D. (2000). Wisconsin Card Sorting Test performance in patients
10 with focal frontal and posterior brain damage: effects of lesion location and test
11 structure on separable cognitive processes. *Neuropsychologia*, 38(4), 388-402.
12
13
14
15
16

17 Szöke, A., Schürhoff, F., Mathieu, F., Meary, A., Ionescu, S., & Leboyer, M. (2005). Tests
18 of executive functions in first-degree relatives of schizophrenic patients: a meta-
19 analysis. *Psychological Medicine*, 35(6), 771-782.
20
21
22
23
24

25 Thomas, M. S. C., Baughman, F. D., & Karaminis, T. (2012). Modelling developmental
26 disorders. In *Current issues in developmental disorders* (pp. 103-134). Psychology
27 Press.
28
29
30
31

32
33 Thomas, M. S. C., McClelland, J. L., Richardson, F. M., Schapiro, A. C., & Baughman, F.
34 (2009). Dynamical and connectionist approaches to development: Toward a future
35 of mutually beneficial co-evolution. In J. P. Spencer, M. S. C. Thomas, & J. L.
36 McClelland (Eds.), *Toward a unified theory of development: Connectionism and*
37 *dynamical systems theory re-considered* (pp. 337-353). Oxford University Press.
38
39
40
41
42
43
44
45
46
47
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Figures

Fig 1. Componential overlay of The Domino Model’s (Fox & Das, 2000) six ‘dots’ and interconnecting arrows onto the Theory of Willed and Automatic Action (Norman & Shallice, 1986). Adapted from Glasspool and Cooper (2013).

Fig 2. Mean perseveration errors (Y axis) produced by the 48 models (X axis). Error bars represent 95% CI). Greyed areas, with dashed lines, depict the PE ranges of target groups extracted from the literature (details in Table B1; supplementary online materials) for controls (CON), healthy first-degree relatives of those with schizophrenia (HFR-SCZ) and individuals with schizophrenia (SCZ). Model 1 (comprised of poorest levels across all EF) exhibited the highest number of PE; exceeding the range of all target groups. Model 48 (highest levels of EF) was close to error-free.

Fig 3. Mean perseveration errors (Y axis) produced by models at each level of functioning (X axis) for each of the three executive functioning components.