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THE CONTROL OF SEMANTIC KNOWLEDGE: EVIDENCE FROM A TASK-SWITCHING INVESTIGATION

Il controllo dell'informazione semantica in un compito di Flessibilità Cognitiva: Un'indagine tramite Task-Switching

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ABSTRACT

The present work aims to investigate and deepen the understanding of the cognitive processes that underpin the appropriate and flexible retrieval of semantic information in a context-appropriate fashion, as well as the specificity of such processes for semantic knowledge.

In particular, our focus will be on the cognitive processes that regulate Cognitive Flexibility, i.e., the ability to skilfully shift our attention and thus switch between two or more mental sets, tasks, and strategies. This cognitive ability is of great importance in day-to-day activities and enables us to adapt to an ever-changing environment with constantly shifting demands, in order to perform purposeful and goal-oriented behaviour and cognition.

Cognitive Flexibility is usually characterised as part of the broader set of Executive Functions that govern Cognitive Control and guide domain-general goal-oriented behaviours and cognition.

However, the cognitive processes that allow us to appropriately shift the focus of attention within the Semantic Representation system and retrieve the appropriate semantic information, relative to the specific context and goals while inhibiting irrelevant associated distractors, have been identified as part of a dissociable Semantic Control system.

Considering the ongoing debate on the interplay between the domain-general executive and semantic control processes, this study aims to further explore the existing relationship between the cognitive mechanisms that regulate Cognitive Flexibility in tasks requiring manipulation of visual-spatial information (domain-general) and those involving semantic content.

This is achieved by employing two tasks of the Task-Switching behavioural paradigm, commonly used to study domain-general Cognitive Flexibility. Although both tasks share the same structure, they differ in the type of stimuli implemented, i.e., one task makes use of visuospatial stimuli typically employed in this paradigm, while the other makes use of verbal-semantic stimuli. All participants performed both tasks and their performances were compared by analysing response times (RTs) and the associated cognitive costs (Switch cost) in both experimental conditions.

The results support the hypothesis that the processes underlying Switching between different tasks, for visual-spatial and semantic information, are not independent and Switch costs show a positive correlation, i.e., participants who are faster at switching in the Executive task are on average faster at switching in the Semantic task.

INTRODUCTION

As human beings, we have a tendency to interpret the world around us; we imbue with meaning objects, people, actions, facial expressions, and perceptions, and through this constellation of information that we accumulate, we make sense of what is happening and predict what has not yet happened. It is by means of this ‘semanticization’ that the cacophony of sounds, shapes, colours, and sensations takes on meaning, and the past, present and future maintain continuity. The collection of this information is organised in an interconnected and adaptable network, where concepts can be retrieved with mastery and ease, based on the requirements of the context and goals of the person, and eventually adjusted and reorganized in the face of contradictions and new unexpected situations.

The most fascinating aspect of this capacity is that we have a whole structure of meaning for things that do not exist in the perceivable reality. Democracy, religions, rituals, are all abstract ideas charged with meaning, but lacking a perceptual reference. We achieve this because much of the semantic information is shared among people and groups, with all due individual and cultural variations, and it is by means of this shared knowledge that we can communicate, understand one another, and predict the actions and intentions of others.

Therefore, we appreciate the pivotal role of these abilities and the value of studying and exploring, how do we construct meaning? Where is all this information stored in the brain? And how do we access this information with such ease?

Building on these questions, we introduce Semantic Cognition, which constitutes the neurocognitive mechanisms underpinning all semantically permeated behaviour and cognition. We begin by presenting the Control Semantic Cognition framework (CSC), initially outlined by Ralph and Jefferies (2017), which provides an adequate theoretical model about the two main subdivisions that characterize Semantic Cognition, while reconciling and summarizing the evidence that has emerged to date from numerous neuropsychological, neuroimaging and neurostimulation studies.

The CSC framework envisages a distributed neural system comprised of two interacting components that draw on different neurocognitive processes and areas, and that together ensure the efficient and appropriate representation and use of concepts, i.e., the Representation System, and the Semantic Control System.

The interaction of these two components within the CSC supports coherent thinking and adaptive behaviour, and the disruption of either of these systems results in qualitatively different neuropsychological conditions with different patterns of semantic impairment.

Thereafter, we will delve into the topic of Cognitive Control responsible for the domain-general control processes and review the most recent evidence concerning the interaction between these two control systems, which are often described and referred to as distinct from one another, but which in more specific analysis, show significant overlapping.

Semantic Representation

The Semantic Representation system outlines the neuro-cognitive structure of the semantic store, which encompasses the collection of all semantically imbued information, including names, physical qualities, history and use of objects, information on how people behave and why, opinions and beliefs, historical events, knowledge of causes and effects, associations between concepts, taxonomic classifications and so on (Binder et al., 2011).

This system integrates, in a hybrid conceptualisation, both the Distributional approaches, which entail learning based on the statistical structure of our multimodal experiences (Andrews et al., 2014) and the Embodied approaches, which assume a strong neuroanatomical substrate for semantic information within sensory and motor cortices (Fernandino et al., 2016).

Specifically, the system features a distributed plus hub structure, defined as 'hubs-and-spokes', in which both amodal representations (i.e., not belonging to a specific modality of experience), based on high-order relations and modality-specific information (i.e., relating to a specific modality of sensory experience) are integrated.

The ‘Hub’ represents information that abstracts from specific features and integrates knowledge related to the different modalities into a unified conceptual amodal representation (Baddeley et al., 2015, p.180), generalized across all contexts.

This centre of amodal representations is presumably located bilaterally in the ventral-anterior-temporal-lobes (vATLs). A possible interpretation for this abstraction process and the relative neuroanatomical localization of the hub is the gradual convergence of information across the adjacent temporal and inferior parietal associative cortices (Binder et al., 2011) up to the most ventral and anterior end of the Temporal Lobes (vATL), which produces a representational gradient along the way and a progressive abstraction from the relative sensory modalities.

Moreover, ATLs are widely connected to all association areas, making them the ideal location for the reduction that information goes through to become amodal (Pobric et al., 2007).
In comparison, the 'Spokes' are widely distributed across different cortical areas and process modality-specific embodied information (i.e., sensory and motor features). Indeed, patients with damage to their motor system (i.e., Parkinson's disease), present impairment in the comprehension of action verbs, likewise TMS stimulation of the primary motor cortex or inferior parietal lobe, produce convergent results (Binder et al., 2011).
By way of illustration, when we think of a 'blueberry', different modality-specific regions will represent specific sensory features, i.e., the blue colour will be represented in colour regions, the round shape in visual-form region, the name in language-specific areas and so on (Patterson et al., 2016). While an amodal representation of the 'blueberry' will be represented in the vATL and will allow us to generalize it to different contexts, distinguish it from semantically similar concepts and recognize it independently of the input modality (Ralph et al., 2017).
Moreover, these areas distributed throughout the cortex engage in bi-directional communication with the hub, and only through this interplay is it possible to obtain semantic knowledge that is so specific and yet adaptable to different contexts, in which information is easily reorganised to have up-to-date and appropriate representations (Ralph et al., 2017).

The most distinctive impairment of the Semantic Representation system is most commonly caused by a variant of frontotemporal dementia called Semantic Dementia (SD), a neurodegenerative disorder caused by ubiquitin-positive/tau-negative inclusion bodies (Hodges et al., 2007) and characterized by a progressive hypometabolism and bilateral atrophy in the vATLs regions, which leads to a gradual deterioration of semantic representations (starting from the loss of more specific information up to more general concepts) across both verbal and non-verbal modalities (Hodges et al., 2007; Jefferies et al., 2008).
The neuropsychological deficits that characterize this group of patients include a gradual disruption of both receptive and expressive vocabulary (i.e., spontaneous speech is distinguished by an increasingly impairing anomia, sometimes referred to as 'loss of memory for words'), person knowledge and appropriate object-use, whereas the repetition of sentences, fluency, phonology, and syntax usually retain normal function (Hodges et al., 2007).
The neuropsychological tasks utilized to verify the presence and severity of the semantic deficit include verbal tasks e.g., picture-naming, word-picture-matching, word-definitions, Camel and Cactus Test (CCT) and also purely non-verbal tasks, such as the image version of the CCT, colour-selection tasks or sound-picture-matching (Hodges et al., 2007). Moreover, SD patients

show, in the early stages of the disease, a relatively normal performance in the letter fluency test (Hodges et al., 2007), which is a measure of executive processes (Shao et al., 2014), whereas they show very limited performance in category fluency, a test more representative of verbal-semantic abilities.

Impairment on these semantic tasks is associated with the severity of the deficit and the extent of the deterioration (Jefferies et al., 2006).

Another aspect that distinguishes the performances of patients with SD is that the responses in picture-naming tasks present coordinate (e.g., zebra→'horse') and superordinate (e.g., zebra → 'animal') errors, with a clear tendency to replace specific concepts with more common and general ones, emphasising the gradual degeneration of knowledge and the profound impact that the specificity of the concepts has on semantic performance (Hodges et al., 2007; Jefferies et al., 2006).

Moreover, SD patients' performances are strongly influenced by the familiarity/frequency of the target concepts, i.e., concepts that are more familiar and frequently encountered tend to be characterized by better performance, arguably because such concepts have stronger and more damage-resistant representations. And lastly, the SD group presents great item-consistency across different tasks, i.e., performance for a specific concept remains consistent regardless of the type of test or input modality, meaning that the representation itself has been lost (Jefferies et al., 2006).

Other evidence corroborating the system of amodal representations in ATLs, is the computational model implemented by Rogers et al. (2004), which simulates this structure and when damaged produced the same behavioural semantic deficits observed in SD.

To conclude, the neuropsychological picture of these patients is of great support for the presence of an amodal hub in vATL, which in this specific condition undergoes a gradual degeneration and leads to an increasingly marked loss of semantic information.

Semantic Control

The second component of the CSC is Semantic Control, which consists of all the processes that regulate semantic activation within the semantic store, allowing appropriate retrieval and flexible manipulation of semantic representations based on a task-appropriate fashion.

To better illustrate the processes through which Semantic Control operates, we can imagine a scenario in which we have to use a tool in an unconventional or rather non-prototypical way, such as using a knife to spread butter on a toast or to open a jar, a pencil as a hair clip or a glass to catch a spider; the execution of the aforementioned operations requires the mediation of the Semantic Control, which by interacting with the representational system, allows the inhibition of the prepotent, well-practised representations (such as cutting for the knife, writing for the pencil and so on), that emerge automatically in our interaction with such objects and direct the activation towards non-dominant and more atypical representations (Chiou et al., 2018).

Therefore, in well-exercised contexts and when we have to retrieve strongly-encoded information, little control is required to model semantic retrieval and produce the correct response, whereas Semantic Control is heavily involved in tasks when we have to process the meaning of ambiguous words that take on different meanings depending on the context in which they are presented (e.g., the word ‘duck’ is a homonym, and its meaning has to be interpreted from the context) (Hoffman et al., 2020), match concepts based on a specific property (e.s., colour) rather than their semantic relatedness (Chiou et al., 2018), or retrieve weakly-encoded information and associations in the presence of strong competing but irrelevant concepts, to fulfil the requirements of the ongoing task (Gao et al., 2021).

When we have to retrieve a concept from the semantic store, activation will spread to other representations that have similar semantic characteristics and that will act as distractors competing for activation along with the target concept, and only through semantic control will it be possible to direct this activation appropriately. The greater the difficulty of the task, i.e., stronger distractors, and more specific target words, the more the semantic control required to produce correct outputs will also increase.

Impairment of the Semantic Control system of the CSC framework results in a neuropsychological condition that has been identified in the literature as Semantic Aphasia (SA) or Stroke Aphasia. The neuropsychological profile of this disorder is characterised by multimodal-semantic impairment and deficits in the top-down control of semantic information, such as poor exploration and manipulation of semantic information, poor inhibition of irrelevant distractors that are strongly associated with the target information and a reduced ability to bring to the fore less dominant aspects of semantic information, although the integrity of the representations is assumed to be maintained (Noonan et al., 2010).

A very interesting aspect is that SA patients present multimodal-semantic deficits across different input modalities and significantly impaired performance with largely equivalent scores in the same semantic tests (e.g., picture-naming, word-matching, word-picture-naming, object use, CCT and so forth) as SD patients. However, the nature of the impairment is qualitatively different and can be investigated with a closer observation of the patterns in their performances and manipulation of the difficulty of the semantic tasks (Corbett et al., 2009; Jefferies et al., 2008).

Above all, the underlying aetiology of these conditions and subsequent lesioned areas are very different. Semantic Aphasia often results from a cerebrovascular accident (CVA) i.e., stroke, usually involving the left frontal and/or temporoparietal regions. Therefore, the locations of brain damage are quite different and hardly overlap because of the inherent anatomy of the cerebrovascular system (ATL receives two arterial supplies), which makes it quite difficult to have a bilateral stroke in the vATL region, that is thus generally immune to this type of damage (Patterson et al., 2007).

Furthermore, an accurate analysis of the deficits presented by SA patients in semantic tasks, highlights several variables and effects that affect performance and that confirm the dissociation between SA and SD, along with supporting the hypothesis that SA deficits do not derive from a loss of knowledge per se, but from an impairment in the access and retrieval of knowledge relative to the goal of the specific task utilized:

- Frequency/Familiarity: SA patients don't display the same facilitating effects of frequency and familiarity that were observed in SD, rather, they might even present opposite effects (Jefferies et al., 2007). This is presumably because the more familiar and frequently encountered concepts have more semantic links and require additional semantic control to inhibit strong competitors and irrelevant distractors.
- Type of error: As mentioned before, during picture-naming tasks, SD patients tend to make mainly coordinate and superordinate mistakes, while SA patients also show associative semantic errors (zebra → 'zoo'), which SD patients do not have. This suggests that SA patients have difficulty rejecting strong irrelevant associations that activate along the target concept (Jefferies et al., 2006).
- Performance within and across semantic tasks: Opposed to the SD group, SA patients show considerably less item consistency between different tasks, i.e., they might be able to retrieve a concept in a task but not in another one that presents different control demands (Thompson et al., 2018). Therefore, they are highly influenced by the nature and type of semantic judgment that is required within a task.
- Cueing: SA patients show positive effects of cueing in their performance. When given a cue, such as the first letter or sound of the word that has to be retrieved, SA patients show a great improvement in their performance. Jefferies et al. (2008) demonstrated how SA patients reached near-perfect performance when given cumulative phonemic cues that

reached or exceeded the target's name uniqueness point, while equivalent phonemic cues resulted in a sensibly more limited benefit to the SD group. 'Cues' represent external support that helps to guide attention to the relevant concept and therefore obtain successful retrieval, only in the cases where the semantic representations are still intact (Jefferies et al., 2006).

- Refractory effects: The performance of SA patients is also characterized by refractory effects, which means that there is a decrease in performance when items that are semantically related are presented successively at a fast rate. A possible explanation is that when semantically related concepts are presented in sequence at a high speed, activation spreads and does not have time to deactivate, while the target concepts become distractors and vice-versa, which makes it more difficult to suppress distractors and requires a higher degree of control (Jefferies et al., 2007).

  Gotts et al., (2002) propose an alternative account, which sustains that there is a failure to overcome synaptic depression after activation, while Schnur et al. (2006) suggest that the refractory deficit is due to an impairment of the verbal selection mechanism.
- Semantic Control manipulations: SA patients show strong effects of semantic control manipulations (Noonan et al., 2010). For instance, by increasing the ambiguity of the target word that has to be retrieved, the strength of the associated distractors, semantic distance between probe and target, we observe a drastic decline in performance, which means that performance is highly related to task difficulty. This also corroborates the multimodal nature of the impairment, since all tasks require some degree of semantic control (Jefferies et al., 2006).

In light of these observations, we can hypothesise with a certain degree of confidence that the disorder presented by SA patients is not caused by a loss of semantic content per se, but a difficulty related to the appropriate retrieval and use of semantic representations. Therefore, items are not degraded, but just inaccessible at that specific moment or task (Almaghyuli, 2013).

From the observation of the lesioned areas in Semantic Aphasia (which, however, remain very extensive and show great variation) and more precisely, through neuroimaging and neurostimulation studies, possible anatomical correlates of the semantic control processes have emerged. Semantic control appears to be supported by a distributed network of areas that presents a strong left lateralisation and includes a strong involvement of the inferior frontal gyrus (IFG), posterior middle-temporal gyrus (pMTG), as well as other areas that also support domain-general control processes, e.g.., medial/dorsolateral PFC and IPS.

However, IFG and pMTG appear to prefer selectively semantic information and cognitively demanding tasks, and not other types of visuospatial manipulations of complexity (Noonan et al., 2010; Whitney et al., 2011; Gao et al., 2021; Chiou et al., 2022). Stimulation of these areas via TMS results in impairment on semantic control tasks, but not on complex visuospatial executive tasks, i.e., Navon task (Whitney et al., 2011).

A critically important aspect to emphasise is that patients with Semantic Aphasia often present very scattered and heterogeneous lesions in both frontal and temporoparietal areas (Souter et al., 2022). Therefore, the resulting deficits are themselves variable and hardly semantic-specific. SA patients generally show deficits that go beyond the multi-modal semantic and verbal impairment, in addition to which they also show severe impairment in attentional and domain-general executive control processes (Jefferies et al., 2006; Thompson et al., 2018).

Cognitive Control

Cognitive Control also known as Executive Functions (EF) encompasses the set of cognitive processes that are intended to support goal-oriented behaviour. However, the neuro-cognitive correlates are still a subject of debate and do not yet present a theoretical consensus.

Our understanding of Executive Functions began through the observation of patients with frontal lesions and the resulting characteristic deficits.

Attentional control, resistance to interference, working memory (WM), information updating, error and conflict monitoring, rule checking, and goal and rule maintenance have been identified as part of the Executive Functions. These processes support and enable multiple higher-order cognitively-demanding tasks such as planning, problem-solving, reasoning and fluid intelligence (Gao et al., 2021; Cristofori et al., 2019), all fundamental to pursue and achieve goal-directed cognition and behaviour, adapt it to fit the specific task or context (Kennedy et al., 2008) and coordinate the flexible shift from one sub-goal to the next one. Cognitive Control is thus opposed to automatic control, which is driven by the environmental setting and elicits prototypical behavioural responses.

The now-historical case of Phineas Gage represents one of the first accounts of executive impairment and provided us with the first insights into the consequences of a frontal lesion.

Subsequent lesion studies and neuropsychological observations have confirmed the importance of the frontal cortex in the correct execution of goal-oriented behaviours, and the coordination of actions for the appropriate execution of complex tasks.

Patients with executive dysfunction tend to perform prototypical and stereotypical actions (i.e., utilisation behaviour) have difficulty interrupting one task to perform another when the context demands it (i.e., perseveration), display extreme rigidity in their behaviour and thinking (Bianchi et al., 1922) and also exhibit socially inappropriate conduct and emotional dysregulations.

Based on these initial observations, EFs have traditionally been associated with the pre-frontal cortex (PFC), hence the executive deficits were initially referred to as Frontal Lobe Syndrome (FLS). The PFC has numerous white matter connections with the rest of the brain, rendering it the ideal structure to play a supervisory and regulatory role over all the other cognitive processes. However, more recent evidence has shown that posterior (in particular the parietal lobe) and subcortical regions also play a crucial role in these higher-order cognitive abilities, i.e., the presence of executive deficits even in the absence of frontal lesions, just as patients with frontal lesions do not necessarily present executive deficits. The neuroanatomical correlates thus turn out to be much more complicated than initially assumed. In light of this new evidence, Baddeley replaced the former label of executive dysfunction with that of Dysexecutive Syndrome (DYS), an umbrella term used to describe a heterogeneous group of patients, but united by a pattern of general executive dysfunction, in cognitive flexibility, reasoning, abstract thinking, planning and behavioural control (Baddeley et al., 1988), usually caused an impairment of the frontal and/or more posterior areas.

The architecture of Cognitive Control is still much debated. Earlier models have theorized a unitary structure of Executive Functions, such as Duncan's Multiple Demand system, thought to respond to difficulty across different tasks, stimulus types and from different sensory modalities (Duncan, 2010), while other theories envisage a set of specialized and fractioned components (e.g., ROBBIA's model of hemispheric specialization). More recent approaches, such as the Miyake model, have proposed a hybrid model of EF, which postulates two partially distinct components, i.e., Updating of WM and Shifting, and a common factor that maintains and organizes goals (Miyake et al., 2012).

This study will focus primarily on an essential component of Cognitive Control, namely Cognitive Flexibility (CF). As mentioned earlier, CF is the ability to appropriately adapt thoughts and behaviour according to changes in environmental demands and is a key process in the control of goal-oriented behaviour.

Specifically, it enables us to skilfully switch from one mental state, representation, or task to another. Cognitive Flexibility is a high-complexity ability that requires the engagement of multiple sub-processes, including appropriate direction of attention (i.e. disengagement from an irrelevant task and redirection of attentional resources to the relevant stimuli and aspects of the new task), maintenance of multiple representations of rules and mental sets in Working Memory (WM), inhibition of previously engaged but no longer appropriate responses, and finally reconfiguration and implementation of the new response appropriate to the new task (shifting) (Uddin, 2021; Anderson et al., 2020).

Neuroimaging literature on Cognitive Flexibility points to a central lore of the Fronto-Parietal Network (FPN) and the Cingulo Opercular Network (CON) in the processes that support executive functioning and CF (Uddin, 2021).

Cognitive Flexibility and the Shifting process is presumed to mobilise both top-down (Dorsal Attentional Network, DAN) and bottom-up environment-driven (Ventral Attentional Network, VAN) attentional resources (Dajani et al. 2015).

The Switching from one condition to the other results in a switching cost, which is the cognitive cost believed to occur due to the time required to inhibit the response set of the previous task and the time required to reconfigure one's response set to the new task.

Cognitive Flexibility is typically measured in experimental settings using the Set-Shifting (i.e., shifting attention between different features of the stimuli to complete the same instruction) or Task-Switching behavioural paradigms (i.e., participants must switch between tasks with different instructions) (Dajani et al., 2015).

When performing the Wisconsin Card Sorting Test (WCST), another classical test used to assess CF, subjects must identify the environmental change by appropriately shifting their attention to the relevant contextual elements, then recognise that the previous strategy is no longer appropriate and thus inhibit the responses linked to it, and ultimately set a new goal and reconfigure a new response strategy (Dajani et al., 2015).

In our investigation, we will use the cued Task-Switching paradigm. The cues anticipate which rule is to be used and accordingly the participant will engage top-down control to direct attention to the relevant features (determined by the criterion) of the stimulus.

Semantic Control vs. Cognitive Control

Given the close neural localisation of the semantic control and domain-general control areas (Jackson, 2021), the absence of a pure semantic control deficit, and the concomitance of semantic and executive deficits in patients with SA, it is reasonable to question whether semantic control processes and executive control processes are independent of each other.

A correlation has been measured between comprehension impairment in patients with SA and their executive dysfunction, which means that patients who present with greater executive deficit, also present with more severe semantic impairment, e.g., a correlation was found between a semantic battery (64 item naming/word-picture matching) and Raven's Matrices ($r > 0.61$, $P < 0.031$) (Jefferies et al., 2006; Jefferies et al., 2008; Thompson et al., 2018), confirming the presence of at least a partial link between semantic control and executive control processes.

The following logical question is to what extent Semantic Control taps into domain-general control mechanisms, and whether it is possible to assert the existence of a separate Semantic Control system specialized for semantic content, or whether the executive deficit is sufficient to explain the semantic deficit observed in SA.

A recent study by Thompson et al. (2018) attempted to explore the link between semantic and executive control processes, confronting the executive and semantic deficits of SA and DYS patients. The SA group was selected solely on the basis of their multimodal semantic deficit (i.e., poor performance on the word and picture versions of the CCT), while the DYS group based on their executive dysfunction (i.e., assessed using the Behavioural Assessment of Dysexecutive Syndrome, BADS).

Then, both groups were subjected to a series of standardised tests to assess executive (Brixton Spatial Anticipation Task (BSAT), Raven's Coloured Progressive Matrices (RCPM) and Digit span, Letter Fluency) and semantic (64-item Cambridge Semantic Battery, Picture Naming, picture CCT/word CCT, 48-item Environmental Sounds Task and the 96-item Synonym Judgement Task) abilities.

Results show that although DYS patients were not selected on the basis of a semantic deficit, they showed parallel semantic control deficits to the SA group (although with minor deficits in both semantic and executive tasks), presented the same distinctive effects (i.e., reduced sensitivity to familiarity/frequency, positive cueing effect, lower item-consistency across tests, sensitivity to task difficulty) and both these groups were comparably discernible from SD patients. A significant effect of executive impairment on semantic performance was then confirmed for both patient groups.

Analogous refractory effects in the absence of aphasia were also confirmed in DYS patients, providing proof to the proposal that the impaired performance in later cycles of refractory tasks can reflect an executive dysfunction (Almaghyuli, 2013).

The similarity between these two groups provides further evidence to the hypothesis that the semantic deficit observed in SA is caused by poor control over semantic retrieval and that domain-general executive control processes are implicated in Semantic Control.

However, there are also some key differences between semantic and non-semantic control; indeed, SA patients have more severe semantic deficits than would be expected from their executive performance, compared to DYS (Almaghyuli, 2013).

Additionally, SA present larger cueing effects, and DYS greater inconsistency across multiple versions of the same task. Such differences could be accounted for by additional damage to multi-modal semantic language representations in SA, which in that case would interact with the control impairments; alternately, it could be explained by possible damage in SA to both domain-general and more specific semantic control regions, which would result in a greater impairment (Almaghyuli, 2013).

As mentioned previously, there is only a partial overlap between the areas related to executive and semantic control and there appears to be a specific increase of activation in IFG and pMTG for tasks that manipulate specifically Semantic Control, and not to other domain-general executive control manipulations. The most intuitive explanation is that these areas are part of a Semantic Control system. While alternative accounts suggest that, although pMTG is not generally considered to be part of the areas aimed at executive control, it has multiple white matter projections with lateral areas of the prefrontal regions and the intraparietal sulcus, regions implicated in domain-general executive control (Thompson et al., 2018).

Chiou et al. (2022) hypothesize the presence of a hybrid Semantic Control system (SCN) that is topographically interposed between the Multiple Demand Network (MDN) and the Default Mode Network (DMN), presenting a mixed response to cognitively demanding stimuli (MDN) and preference for meaningful information (DMN).

On this theoretical grounding, our aim will therefore be to explore this currently ambiguous relationship.

METHODS

Participants

The experimental sample is composed of 202 healthy participants, whose ages ranged from 18 to 57 years (M= 23.7, SD=6.1), of which 69.8% (141) identified as female and the remaining 30.1% (61) as male.

Before starting the experiment, participants were asked to complete a hand dominance questionnaire, which resulted in 18 left-handed, 9 two-handed and 174 right-handed.
All participants completed both the visuospatial and the semantic task-switching.

Experimental Design

All participants completed the battery of tests divided into 3 separate sessions, each lasting on average 30-40 minutes. Each session consists of short tasks (lasting from 4 to 10 minutes) of varying difficulty. The time required to complete the experiment varies according to the performance of the participants and the duration of the pauses between tasks, which are left to the discretion of the participants (however, it is suggested not to let too much time pass between tasks), and the time passed between sessions (this is also left to the discretion of the participants, as long as the three sessions were completed over the period of one week).
During each of the three sessions, the percentage of completion is shown in real-time.
For the experiment to be valid, the three sessions had to be completed in their entirety in the order given and within the time-frame indicated.
The experiment was completed entirely online on the computer/tablet, using a physical keyboard.

This study took in exam two of the tasks from the test battery. The tasks are two versions of the cued Task-Switching behavioural paradigm. Each task lasts approximately 8 minutes depending on the participant's performance.
The tasks have the same structure and vary only in the type of stimuli utilised. The first is an Executive Task-Switching which employs visuospatial stimuli (i.e., coloured geometric figures), while the second is a Semantic Task-Switching which uses verbal semantic stimuli (i.e., written words).

The stimuli used respectively in the Executive task and Semantic task were fixed, what changed was the rule according to which the response decision had to be made.

Each session of the experiment began with the presentation of a screen introducing a set of rules and suggestions (with visual representations) on how to carry out the experiment optimally. Participants were told to centre the computer screen relative to the direction of their gaze, to mute all devices that could be a potential source of distraction, to carry out the experiment in an environment free of visual or auditory distractions, to keep their fingers in contact with the keyboard at all times while carrying out the task, and to assume a comfortable position to avoid fatigue and discomfort.

Participants were instructed to place both index fingers on the keyboard. The left index finger on the C key and the right index finger on the M key. Whereas the space bar was pressed with one of the thumbs to move forward during the instruction and training phases.

After reading the rules, participants could press the space bar to start the experiment session.

Executive Task-Switching

The visuospatial stimuli used in the Executive Task-Switching were single-coloured geometric shapes that could vary according to two features: SHAPE (square; diamond) and COLOUR (red; blue), which also represented the possible decision criteria.

The number of total stimuli used in the Executive Task-Switching were four: red-square, blue-square, red-diamond, and blue-diamond.

Both executive and semantic tasks were divided into three successive blocks, each introduced by a screen presenting the rules and decision criteria for that specific part of the task and a training phase with response feedback indicating whether the answer given was: Correct, Incorrect, or Missing. The training phase was considered passed when an accuracy level of 75% was reached, with a minimum of 10 trials and a maximum of 32 trials.

The first two parts of the task are single blocks which function as control. The first part of the Executive Task-Switching was a single block labelled: SHAPE, in which one of the four visuospatial stimuli was shown and participants were asked to indicate its SHAPE by pressing the C key if the shape was a ‘square’, and the M key if the shape was a ‘diamond’. The second part of the task was a single block, labelled: COLOUR, which was largely similar to the first one, but the decision criterion was changed. Participants were instructed to press 'C' if the stimulus that appeared was 'red' and 'M' if the stimulus was 'blue'.

Each trial of the Single blocks consisted of two screens. An initial fixation screen (blue background and black central fixation cross) was presented for 1000 ms. This was followed by a screen with one of the four possible visuospatial stimuli at the centre, which was maintained until the participant did not provide a response (if more than 2000 ms passed without a response, then it was considered 'Missing').

The third part was a Mixed block, which measures the actual task-switching ability, and will be used for the data analysis, labelled: SHAPE or COLOUR?

Participants were asked to evaluate the stimuli according to one of the decision criteria used in the previous two phases. For each trial of the mixed block, the fixation screen was followed by the presentation of a cue ('SHAPE' or 'COLOUR') which represented the response criterion that had to be used for the immediately following stimulus. The screen cue persisted for a duration of 300ms.

Between each trial of the Mixed block, the response criterion could remain the same (Repeat-trial) or change (Switch-trial). The latter represents the actual Switch and the mechanism of interest for the analyses.

In the Mixed block, only the 'ambiguous' stimuli with contrasting characteristics were used (red-diamond and blue-square). These ambiguous figures require the use of different keys when changing the decision criterion (diamond=M, blue=M, square=C, red=C). Therefore, preventing an answer from being mistakenly registered as Correct in the switch trials while we were using the previous trial rule.

Semantic Task-Switching

The semantic task-switching had the same structure as the Executive Task-Switching but varied in the type of stimuli utilised.

The semantic task-switching employed verbal semantic stimuli belonging to four semantic categories: animals, plants, objects, and vehicles. Each semantic category consisted of 12 concrete words, for a total of 48 verbal semantic stimuli, selected from the Italian semantic norm (Montefinese et al., 2013).

The stimuli were presented in the centre of the screen as words with bold formatting, font size 44, calibre font and black colour.

As well as in the executive version, there were initially two Single blocks that function as control and successively one Mixed block.

The first Single block was labelled: LIVING/NOT LIVING and consisted in deciding if the appeared word was representing a living or not living concept, by pressing the C key if LIVING and the M key if NOT LIVING.

The second Single block was labelled: MOVING/NOT MOVING and consisted in deciding if the appeared word was representing a moving concept by pressing C or NOT MOVING concept by pressing M.

The Mixed block presented alternating response criteria anticipated by the correspondent verbal cue, presented as a question. If the cue was MOVING?, then participants would have to press C if the concept can move and M otherwise. While if the cue was LIVING?, then participants would have to press C if the concept was living and M if not.

As for the Executive version, only ambiguous stimuli (i.e., pertaining to the plants and vehicles categories) were presented in the Mixed block, because require different combinations of keys to respond and therefore cannot determine a Correct response with the criterion of the previous trial.

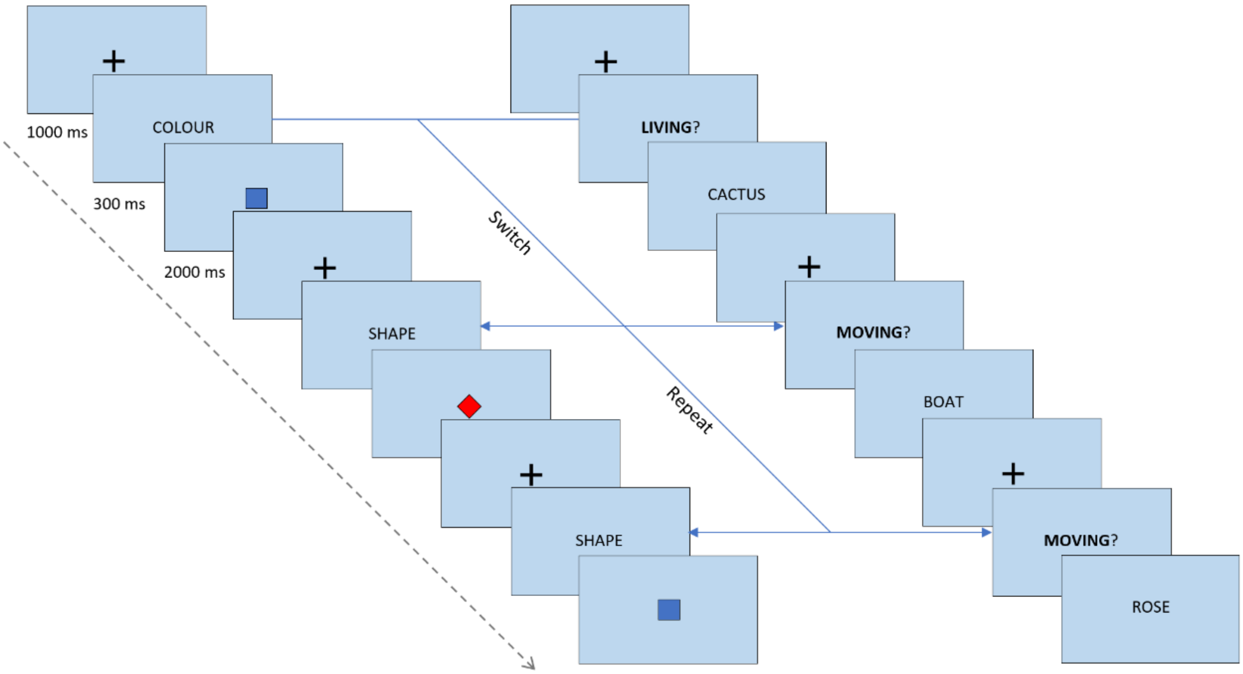

Figure 1. Executive Task-Switching (left) and Semantic Task-Switching (right) progression. Switch Trials when the cue and therefore the response criterion changes; Repeat Trials when the cue, i.e., response criterion, remains unchanged.

Procedures

Participants for the study were recruited mainly among students from the University of Padua's Faculty of Psychology, who were offered a bonus on an exam, in return for taking part in the study. In addition, researchers' personal affiliations and social platforms were used to recruit other participants, offering the possibility of winning a prize in the form of Amazon vouchers if ranked first, second, third or fourth (ranking was based on performance, i.e., response times and percentage of correct answers, and was intended to encourage participants to carry out the experiment accurately and with focus).

Participants were given access to the experiment by clicking on a hyperlink provided in the recruiting announcement, which redirected them to a webpage containing a brief overview of the study, the technical specifications (necessary devices to perform the experiment), eligibility criteria (being over 18 years old and being an Italian native speaker) and lastly, the contact details.

Afterwards, participants were asked to give their informed consent and a series of demographic information, including their age, gender, level of education and e-mail address in order to be sent the results of the experiment, however, this information was not compulsory to be able to carry out the experiment.

Participants were free to terminate their participation in the study at any time. The data considered later in the analysis included exclusively the data of those who completed the experiment in its entirety within the indicated time frame.

The experiment was created using PsyToolkit (Stoet, 2017; Stoet, 2010; www.psytoolkit.org).

Data Analysis

The main variable measured were the response times (RTs). A peculiar property of response times (RTs), which makes them particularly challenging to analyse, is that they do not have a normal distribution. Hence, to simplify the process, RTs were transformed into response speed (RS) using the formula 1000/RT. The negativity sign was then added to make this new value more intuitive, with a lower value corresponding to a shorter response rate measurement.
Therefore, lower speed response values reflect shorter and accordingly more efficient responses.

An initial filtering of the data was carried out to discard all trials of the training sub-blocks, trials with incorrect responses (6.8%), missing responses (1.2%) and those with RTs of less than 200 ms (0.1%).
An initial filtering was performed via Excel and subsequent analyses via Jamovi 1.6.15 software.

The experimental design was within subjects on repeated measures. We initially performed a two by two (2x2) Repeated Measures analysis of variance (ANOVA) to investigate the presence and intensity of the TRIAL effect (Repetition vs. Switch), i.e., cognitive cost of Switching between the two different rules, the STIMULI effect (Semantic vs. Executive) and the interaction between these two conditions.
A subsequent analysis was performed to investigate the relationship between Executive and Semantic control at the level of Cognitive Flexibility. First of all, the switching cost for each two mixed blocks, executive and semantic, was measured by subtracting for each participant the mean Response Speed (RS) of Switch trials from the mean speed of Repeat trials (we have to remember that RTs have been transformed in Response Speed).
Successively we calculated the correlation coefficient between these two variables and then performed a single-sample t-test, to analyse how the two switching costs variate together.

RESULTS

Repeated Measures ANOVA

The Repeated Measures ANOVA revealed a significant effect of TRIAL (Repeat vs. Switch) ($F(1,201) = 724.14$, $p < .001$, $\eta^2_p = 0.78$) and a strong effect of interaction ($F(1,201) = 405.78$, $p < .001$, $\eta^2_p = 0.67$). The effect STIMULI (Executive vs. Semantic) also resulted significant, yet not as strong ($F(1,201) = 4.62$, $p = .033$, $\eta^2_p = 0.02$).

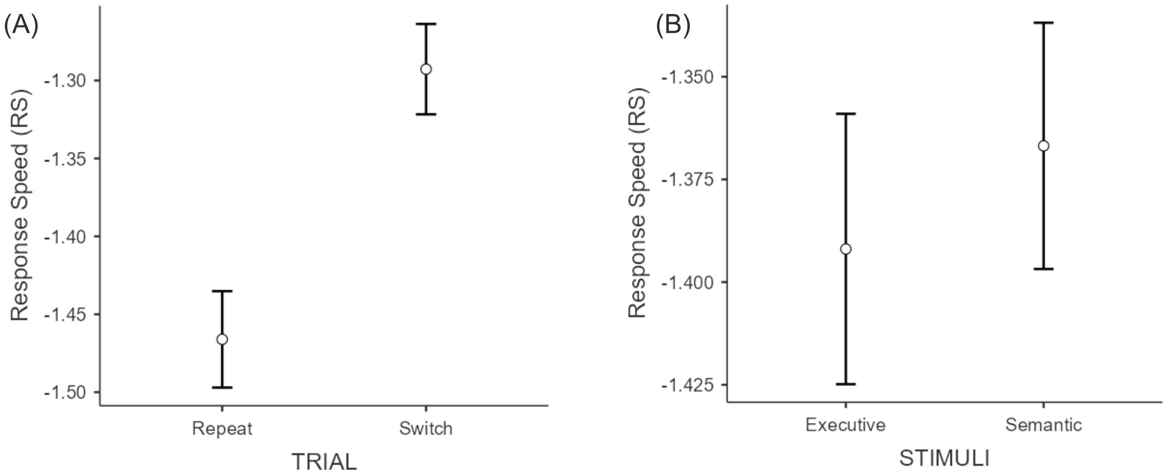

Figure 2. (A) Difference in Response Speed (RS) based on the type of TRIAL (Repeat vs. Switch). (B) Difference in Response Speed (RS) based on the type of STIMULI utilised (Executive vs. Semantic).

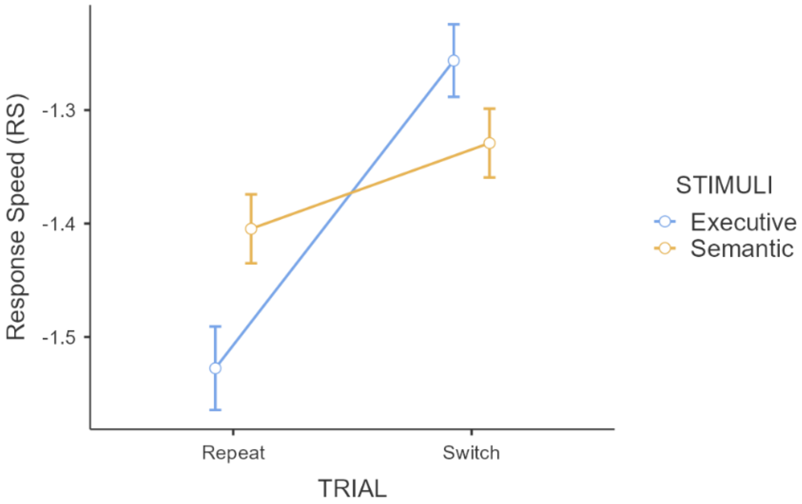

Figure 3. Interaction between the two experimental manipulations: TRIAL (Repeat vs. Switch) and STIMULI (Executive vs. Semantic). In the Repeat trials, RTs are shorter for Executive stimuli, i.e., responses are faster. There is a stronger Switching cost for the Executive stimuli, (i.e., slower RTs for Switch trials compared to Repeat trials) compared to the Semantic stimuli.

Correlation and Student's T-Test

The correlation between Executive and Semantic switch cost resulted significative for both Pearson's correlation coefficient r (202) = .36, p < .001 and Spearman's correlation, p (202) = 0.23, p < .001.

The paired sample T-Test between the two switch costs also resulted significant t (201) = 20.14, p < .001 implying a relationship between the two data sets.

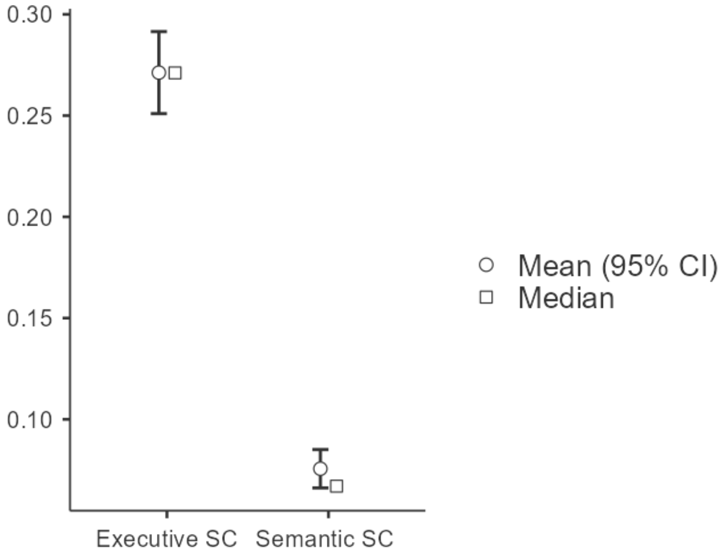

Figure 4. Mean, Median and Standard Deviation (SD) of Executive Switch Cost and Semantic Switch Cost. Executive Switch costs are much higher (M = 0.27) than Semantic Switch costs (M = 0.07).

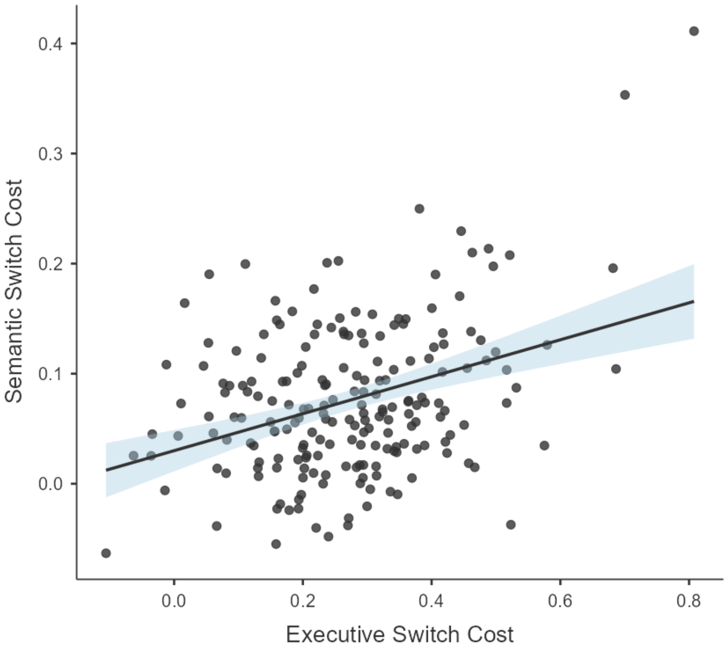

Figure 5. Scatterplot graph of the distribution of Switching costs in Semantic (Y) and Executive (X) conditions and relative Standard Error (SE).

DISCUSSION

The present study had the goal of investigating the relationship between the processes that regulate Switching between two task-sets, employing respectively visuospatial and semantic stimuli, and investigate whether the processes that regulate these abilities are independent of each other.

We accomplished this by using two cued Task-Switching behavioural paradigms, similar in all aspects except for the type of stimuli employed.

The first Task-Switching task made use of visuospatial stimuli, which are commonly used to investigate Cognitive Flexibility and Switching as part of Cognitive Control and domain-general processes. Whereas the second Task-Switching task used verbal-semantic stimuli.

We then collected Response Times (RTs) as the main dependent variable and analysed the differences and interactions between the two performances, by comparing the relative Switching costs and looking for effects on performance of Stimulus type (Executive vs. Semantic) and Trial type (Repeat vs. Switch).

In first instance, we performed an analysis of variance (ANOVA) and checked for STIMULI type (Executive vs. Semantic) and TRIAL type (Repeat vs. Switch) effects, and their corresponding interaction.

A strong and significant effect of TRIAL type (Figure 2. A) was found, which is representative of the cognitive cost (Switch Cost), associated with Task-set reconfiguration, and is characterized by an increase in Reaction Time (RT) and decrease in accuracy (however this variable was not considered in our analysis) (Kiesel et al., 2010) in Switch trials compared to Repeat trials. This result is in line with previous evidence on the topic (Monsell, 2003) and confirms our expectations, further supporting the presence of a cognitive cost when switching from one task to another.

The effect of STIMULI type (Executive vs. Semantic) was also significant, although less strong. RTs in the executive Task-Switching were on average shorter than those recorded in the semantic Task-Switching, suggesting that the processing of visual-spatial stimuli may have an advantage over the processing of semantic information (Figure 2A). The visuospatial stimuli employed in the study (coloured geometric shapes) represent simple visual inputs with basic features that primarily engage visual sensory cortices, conversely, the verbal semantic stimuli involve more extensive brain networks and therefore take longer to process adequately.

We will elaborate on the effect of the stimulus on performance later by considering the interaction between the two variables.

A possible variation of the experiment using non-semantic verbal stimuli (i.e., meaningless strings of letters) for the executive task could mitigate this effect of processing speed. Furthermore, a significant interaction effect was found between TRIAL type and STIMULI type. As can be seen in Figure 3, which illustrates the interaction of the conditions, in the Repeat trials the RTs for the Executive task were considerably shorter than those observed for the Semantic task. This means that participants responded more quickly to the Executive task, emphasising the greater complexity of the Semantic task.

By contrast, the RTs are both considerably high in the Switching trials for both stimulus conditions. To some extent, we expect a ceiling effect for Reaction Times in the Switching trials, as RT can only increase to a certain point before reaching a plateau. What remains unclear and needs further consideration is how considering the RTs in the Repeat trials (Semantic RTs > Executive RTs), we then observed in the Switch trials (Executive RTs > Semantic RTs).

A possible interpretation of these results is that in the Switch trials of the Semantic task, two processes intervene to support task execution and switching between conditions: domain-general executive processes that maintain the goal and sustain goal-reconfiguration (Task-set), and semantic control processes, which guide attention in the representation semantic system and help to retrieve the concept and its semantic features. The combined action of these two processes would then allow to select the correct behavioural response. If this was the case, this collaboration between executive control and semantic control processes could explain the reduction of the RT found in the Switch trials of the Semantic condition, that in contrast to the Executive one, would see two systems come into play, making operations faster and more effective. This interpretation would be in line with previous evidence that suggests an intervention of domain-general executive processes in the manipulation of semantic information.

A second possible explanation for these results derives from the methodological implementation of the experiment and the presentation format of the cues in the mixed block of the Semantic task, such that cues were displayed as a question (LIVING? / MOVING?), to which participants could form implicit/explicit association to simple responses, yes/no (i.e., if the answer to the question (cue) was yes, C key had to be pressed; if the answer was no, then M key had to be pressed), hence creating a facilitation effect for the responses in this condition and determining faster RTs. A possible solution to this problem would be to change the mode of presentation of the cues in the two conditions and to make them more homogeneous.

In a subsequent correlation analysis, a significant positive correlation was found between the Executive Switch cost and the Semantic Switch Cost (Figure 5), although the was a substantial difference in the two measurements (i.e., Executive Switch costs were much higher than Semantic Switch costs, Figure 4).
This means that participants who displayed shorter RTs in the Executive task tended to have shorter average RTs in the Semantic task as well, casting further doubt on the independence of the processes involved in these tasks.
An additional paired sample T-Test of the Executive and Semantic Switch costs resulted significant, further confirming the relationship between these two processes.

In conclusion, our results support the hypothesis that shifting from one visuospatial task to another, as well as from one semantic task to another, involves processes that share a common cognitive basis and are therefore not independent of each other. However, the extent to which these processes are linked, and the nature of their connection remains unknown. In fact, just as it is not possible to assert a total independence of the processes, neither is it possible to assert their total equivalence, as there are differences in the performance of the two tasks, that still need to be investigated more meticulously.
Among the implications related to the relationship of these control processes, it would suggest that the deficits described in SA patients may be relatively widespread even in patients with different aetiologies that present executive deficits (Thompson et al., 2018), revolutionizing the diagnostic criteria and the related therapies and interventions to be implemented.

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