Executive Function and Intelligent Goal-directed Behavior: Perspectives from Psychology, Neurology, and Computer Science

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Abstract. The concept of executive function, as top-down control of processes, originated in computer science in the 1950s. However, it has since become an important concept in a range of human sciences, particularly for its explanatory power in psychology, education, and clinical neurosciences. Nevertheless, its use has been limited by vague definitions and confusion between the related conceptualizations of executive process and intelligence. Here we explore the concept of executive control in detail, drawing on psychology, neurology, and computer science / human-machine interaction. We describe the core goal-directed and resource-limited features of executive control, its fractionation into components, and partial overlap with psychometric conceptions of intelligence. We also examine its associations with neurological systems beyond those usually linked to executive function (i.e., the front lobes). We propose that executive functions are 'intelligent', and can be defined by their goal-directedness. Furthermore, executive function tasks can be classified by their task goals into one of three types: Those that involve i) convergent, or ii) divergent thinking, or iii) not responding, such as in psychomotor response inhibition. Conventional intelligence tests measure only convergent thinking. The recognition of non-convergent executive functions allows the identification of executively controlled intelligent goal-directed behavior beyond that controlled by domain-general cognitive processes. This reconceptualization may benefit research in education, clinical and cognitive sciences, as well as the quest for artificial general intelligence.

Keywords: Executive Function, Cognitive Control, Divergent Thinking, Intelligence, Neuroscience, Frontal lobes, Human-computer interaction

1 The Origins of Executive Function as a Concept

Although now a well-known expression in psychology and neuroscience, the original conception of executive processes came from the need to coordinate aspects of programs running on computers. In 1956, an early attempt at control of programs, essentially batch processing, was referred to as 'Automatic Supervisor' for the IBM 702 computer [1]. This approach was developed into what may be one of the first ever operating systems, designed by General Motors for the IBM 704, the GM-NAA Monitor [2], also known as the General Motors Executive System. Subsequent operating systems had more explicit executive control, particularly FACT in the late 1950s (designed to run on the Honeywell 800 computer). This included a system described as an Executive Schedule and Monitor, which was an operating system that coordinated the running of programs: locating them on tape reals, checking they could run simultaneously, allocating memory resources, starting, restarting (if necessary) and stopping programs, and adjusting program run schedules [3]. Through the early 1960s many other operating systems were developed which used similar principles, and had names such as University of Michigan Executive System, Exec 1, Master Control Program, Executive, and Supervisory Control Program [2]. This technology, invoking top-down control of computers, coincided exactly with the 'birth' of cognitive science in 1956, a field which explicitly drew on computer science in order to understand the mind [4].

Thus, the concept of executive control was adopted by cognitive science, and is now an intensely studied field of human and non-human cognition, spanning multiple academic disciplines, including psychology, neuroscience, and linguistics. In addition, it has been adopted by many applied fields to 'explain' aspects of behavior. These applied aspects include education, neurology, psychiatry, and human-computer interaction.

1.1 The Utility of Executive Functions as a Concept in Human Sciences

Within human sciences, executive functions are generally defined as being cognitive processes that guide behavior when deliberate, attentional selection of response options is necessary, such as inhibiting behavior, switching between tasks, or dealing with novel situations. In particular, executive processes have been explored as top-down controllers of routine cognitive processes. Although intelligence test scores, as a measure of overall cognitive ability, are a good predictor of performance in education in general [5, 6] researchers have highlighted the specific contribution of domain-specific cognitive abilities which associate with achievement in specific subjects [7, 8]. These include the commonly identified executive functions of working memory, inhibition, and task switching / flexibility [9-11]. Cognitive flexibility is the ability to switch from one activity to another, or to go back and forth between activities, redirecting our attention and planning actions that allow us to achieve a goal. It allows people to experience and learn from different perspectives, being aware of their own mistakes, and to take advantage of unexpected events [9]. It may be the most important executive function relating to school performance, particularly for reading and mathematical achievement [11]. Working memory is a supposed central system for processing and temporary storage of information which will be used to perform cognitive tasks of varying complexity

[12]. It is linked to student success in language learning and mathematics [8] and science [7], as well as good classroom behavior [13]. Response inhibition is the ability to voluntarily restrict a dominant or instinctive response triggered by a stimulus. It has been found to be a good predictor achievement in school in general [13], including in higher education [6]. Furthermore, executive functions allow students to process material, to focus and maintain attention, and, importantly, adapt a socially accepted behavior according to the cultural context [11]. Diamond suggests that these cognitive abilities are essential for success in school because they ‘make possible mentally playing with ideas’ [9, page 135]. Consequently executive function ability is seen as more important for success in school, and later in life, including physical and mental health, than intelligence or the socioeconomic background of individuals [14].

One reason for the strong links between executive function and ability to learn is that the neurodevelopmental condition- attention deficit/hyperactivity disorder (ADHD), is defined by difficulties with cognitive control. In fact, problems with executive functions are observed as symptoms in almost all neuropsychiatric disorders, including neurodevelopmental disorders (such as ADHD), neurological and psychiatric disorders [15]. They may also be risk-factors for clinical problems such as substance dependence [16] and deliberate self-harm [17]. Beyond education and clinical applications, executive functions have also proven to be important correlates or multiple life-challenges, being particularly sensitive to poor sleep quality, loneliness, sadness, being physically unfit etc. [9]. They also predict workplace performance better than intelligence does [18] and help to explain failures of human-machine interaction [19]. Consequently, this once obscure concept originating in the rarefied world of computer architecture is now of interest across a range of academic, applied, and clinical human sciences.

1.2 The Psychological Background to Executive Functions

The term ‘executive function’ was first used within psychology, with a meaning similar to how it is currently used, in 1967, by the psychologist J.P. Guilford. He suggested that executive function provides ‘a link between cognition and action in behavior’ [20, page 294]. In his attempts to classify the range of human cognitive processes based on statistical associations he noted a ‘set of executive abilities, concerned with putting ideas into action through implied intention’ [21, page 35]. And with the ‘organization and control of motor output’ [22, page 99]. The concept of executive function has since developed within psychology, particularly from a cognitive perspective. The modern use of the term describes a wide-range of process and abilities that appear to operate in a top-down fashion to control other cognitive processes, and ultimately behavior. There have been multiple cognitive models provided, but two main approaches have dominated cognitive theory in this field, the Supervisory Attentional System provided by Tim Shallice and colleagues [23-27], and the Working Memory model provided by Alan Baddeley and colleagues [12, 28-32].

The Supervisory Attentional System. In 1980 Norman and Shallice proposed a model of the automatic and willed control of human behavior that involved two systems. Firstly, the Supervisory Attentional System is active in the control of behavior in situations that are novel, dangerous, or require planning, or complex procedures that have not yet been learnt [24].That attentional mechanism acts to bias selection of action schemas that already exist. However, appropriate behavior can usually be achieved when it is triggered by perceptions and controlled by schemas, based in memory, that interact through excitation and inhibition to select the most appropriate response. This schema-based system of activation is known as Contention Scheduling and instigates well-learned, procedural, and habitual actions. This model has developed, but is still widely accepted and applied as a model of the executive control of action and thought [24-27]. In this model, executive processes are carried out by the 'general purpose, limited-capacity mechanism', that is, the Supervisory Attentional System, while the routine Contention Scheduling System does not have central processing limitations [24, page 12]. Shallice drew on early artificial intelligence research on problem solving that used tasks with clear goals, that would require the task decomposition into sub-goals extending his theory into human planning ability and executive functions more broadly [25].

Working Memory. The dominant model of human memory, proposing separate long-term and short-term stores, originally invoked a number of control process within the short-term store [33]. However, this was unable to explain a range of experimental observations, and in 1974 Alan Baddeley proposed a limited capacity Central Executive, separate from short-term memory storage [12]. This allowed the dual-memory system model to explain many more observations. Nevertheless, in early versions, the Central Executive component was only vaguely described. When the Supervisory Attentional System was proposed by Shallice at al., this was adopted as the theoretical basis for the Central Executive of Working Memory [28, 29]. A main difference between the models is simply the emphasis on what is controlled by the executive component. In Working Memory it is temporary memory systems, in particular, a phonological store and a visuospatial store [12, 28-31], and an episodic buffer [31, 34]. The Central Executive is proposed as an attentional mechanism, lacking storage capacity, that is responsible for coordination of processing between different tasks [28, 32], focusing processing on information from different sources, and manipulating and modifying information [34].

1.3 The Neurological Background to Executive Functions

It has long been observed in neurology that brain damage can produce disorganized behavior. A famous case being Phineas Gage, who, in 1848, suffered a brain injury in an industrial accident. Although he survived the injury, his behavior became erratic, with difficulties in planning, decision making, and disinhibition. Although his cognitive ability was sufficiently intact for him to work, he changed occupations frequently. His doctor said that 'his mind was radically changed' [35, page 277]. From examination of his skull, it is known that the brain damage was limited to the prefrontal cortex, mainly of the left hemisphere [36]. A modern case that has been reported, who survived a similar injury to the left prefrontal cortex, was able to pass many cognitive tests and had an IQ well above average. But like Phineas Gage, he suffered a disorganization of behavior, including chronic unemployment and relationship instability [37]. Many other patients have been reported in the clinical neuroscience literature with damage to the frontal lobes resulting in disorganization of behavior manifest in occupational and educational instability, despite normal or above average IQ, [26, 38-40].

This disorganization of behavior, following damage to the frontal lobes, appears to reflect impairment of top-down cognitive control, the processes associated with executive functions. In 1973, drawing on computer science, and the need for programs to coordinate information-processing demands with a central processor, Karl H. Pribram proposed that the frontal lobes of the brain may function in that way. Thus, 'executive programs' were proposed as a means for the brain to handle competing processing demands, and damage to the frontal lobes disturbs that control [41]. Such behavioral syndromes in neurology have been increasingly interpreted as reflecting an impairment of executive control, and are now often known as the dysexecutive syndrome [42].

This association between the frontal lobes and executive control has become widely accepted, due to multiple reports of executive function impairments, following damage to the frontal lobes of the brain [23, 25-27, 35-38, 40, 42-47]. Although it is true that such an association exists, it provides a seductive but overly simplistic pseudoscientific reduction of process to physiology that has been referred to as 'frontal lobology' [48]. Additionally, the frontal lobe cortical systems which control behavior operate through other brain regions, particularly circuits involving subcortical structures which include input from other cortical regions, particularly the parietal lobes [49]. These circuits operate as loops, with the initiation of a simple goal-directed action, such as a finger movement, likely involving at least 20 passes through the frontal-subcortical loop [50].

Accordingly, brain imaging has identified a system involving selective areas on the frontal lobes, as well as the parietal lobes, and linked subcortical structures, which appears to have a domain-general function (i.e., it responds to tasks regardless of task type -visuospatial, language, auditory etc.) [51-53]. This system is said to allow the representation of goals from diverse tasks, and to be the physiological substrate of both general intelligence and at least some aspects executive function. A popular functional description of this brain network is as a multiple demand system [51, 52]. However, there may be several domain-general processes that overlap in performance of any given task, and it is these domain-general processes that are described as executive [54].

In addition, the brain's default mode network appears to be functionally linked to executive functions. That network comprises a set of frontal, parietal and temporal lobe regions that are active during rest but become deactivated when performing executive-demanding tasks [55, 56]. The default mode network likely plays some active role in cognitive executive control [57] and may also coordinate action-schema maintenance [58, 59].

Semantic cognitive control is also a theme that has emerged recently. Neuroscience research using multiple methods has suggested that in addition to semantic representations in the brain, there is a system for executive control of semantic information. This semantic control network in the prefrontal and parietal regions (already closely linked to executive functions), but also regions of the temporal lobe, is involved with goal-directed control of the processing of lexical information [60].

1.3 Computer Science and Human Executive Functions

We have previously computationally modeled human executive functions for both Shallice's Supervisory Attentional System and Baddeley's Working Memory models [19, 61]. We have implemented these models with Behavior and Reasoning Description Language, based on Real-time Maude, a language developed to model human reasoning within the context of intentional (executive) and automatic action [62]. In this approach, deliberate attentional action is modelled by task goals (equivalent to the role of the Supervisory Attentional System) and based on declarative semantic knowledge. In contrast, automatic behavior is based on knowledge in procedural memory stores [63].

Part of the motivation behind these in silico models is to understand intentional and automatic aspects of human-computer interaction. Executive functions play an important role in the way users interact with computer interfaces as well as with any machine interface, and especially when they carry out articulated tasks which involve interactions with multiple interfaces of embedded computer systems. This can be the case of both routine activities occurring in ordinary daily life, such as driving, and work-related activities of operators of control systems, such as air traffic control, industrial machine, medical device, and control room operators. Tasks such as these have safety-critical aspects but are normally carried out under automatic control. Moreover, they may involve multitasking (an operator often has to monitor a number of distinct readouts simultaneously) or, being performed under automatic control, may actually encourage multitasking (drivers often listen to music or talk, or even unsafely use mobile phones, while driving). In such contexts the role of an executive controller is fundamental in changing the behavior control from automatic to intentional when required by sudden changes in the environment and, if such changes determine hazards, in preventing dangerous situations or the violation of safety requirements. We have considered typical situations that activate the Supervisory Attentional System[19]:

required decision which may be needed in the normal operation of the system;

expectation failure when the user/operator's expectations are not met;

emotions determined by something perceived through implicit attention.

Expectation failures requires conscious assessment, normally in terms of novelty or hazard, to drive the intentional behavior that must be carried out to cope with them. Typical emotions are curiosity, temptation, and anger. They not only trigger emotional reactions, but they normally necessitate the establishment of new goals, hence intentional behavior. For example, while driving under automatic control, we may need to resort to intentional behavior in each of the above situations. When we are at a crossing on an unfamiliar route, we must consciously evaluate the directions given by the road signs and make the appropriate decisions. An expectation failure could be a strange sound from the engine, to which we may consciously react by slowing down and possibly stopping the car, or a deviation signal on a familiar route, which make us consciously planning how to best reroute. Finally, several emotions may be triggered by events we encounter while driving. Curiosity may be triggered by the presence of police and emergency vehicles on the road. A temptation may be represented by the sight of a stall selling some food we are craving for, which may urge us to consciously stop to purchase it. Anger which may be caused by another driver honking to ask for space to overtake and may result in several possible reactions, usually inappropriate and, sometimes, even associated with conscious revenge.

Our previous work [19] also considers contention scheduling. For example, in the case of driving, the driver's behavior while approaching an amber light. In this situation, the driver has two possible responses: (1) stop at the traffic light; (2) speed up. The driver's behavior is determined by the activation of the schema-based Contention Scheduling System. Depending on the behavior learned through practice, which resulted in the creation of a procedural, habitual schema that consistently instigates the driver to either stop or speed up, without a proper evaluation of which of the two responses is safer. Although the two schemas may both be present in the driver Contention Scheduling System, the actual choice that leads to the contention resolution is not determined by a proper evaluation of the situation, but by a mental state. For example, a driver who is in a hurry is more likely to choose to speed through the crossing.

2 Current Issues and Controversies Regarding Executive Function

2.1 Is There a Unitary Central Executive?

Both of the models presented here, the Supervisory Attentional System [23-27] and Working Memory model [12, 28-32, 34], are usually represented with a single, central, executive process. However, it is reasonable to think that the theorized 'executive' may fractionate into different components. Alan Baddeley has suggested that this is likely about his Working Memory model [28, 29, 34], as has Tim Shallice about his Supervisory Attentional System [25], in fact he has recently presented evidence that different forms of brain damage produce qualitatively different impairments of the Supervisory Attentional System [27]. Similarly, it has been argued that executive processes, such as task setting, energization, and behavior monitoring may be independently impaired by damage to the frontal lobes. The authors conclude that there can be no cognitive 'central executive', nor a unitary neurological 'dysexecutive syndrome' [64]. Similarly, an analysis of the brain regions indicated in functional imaging studies, radiological studies of brain injured patients, and split-brain patients that lack corpora callosa (the main connections between the brain's hemispheres) have been said to provide no evidence for a single central executive neurocognitive mechanism [65].

Furthermore, from cognitive psychology, research comparing test scores from healthy participants has shown that many executive function test scores barely correlate, suggesting they are measuring independent processes [66]. From a psychometric perspective, clusters of task-performance scores have been analyzed, with one important study suggesting both 'unity and diversity of executive functions' [10]. Clearly, there is some controversy of which abilities and tasks should be considered 'executive'. This is partly because the definition of executive control is rarely considered in detail.

2.2 What is, and What is Not, Executive Function?

The concept of executive function has developed mainly within psychology, albeit with substantial influence from artificial intelligence. Within neuroscience, a similar concept is known as cognitive control. However, these are generally used interchangeably, and both can be defined as 'the ability to coordinate thought and action and direct it toward obtaining goals' [67, page 99]. A classic definition has been that 'Executive functions are high-level cognitive processes, often associated with the frontal lobes, that control lower level processes in the service of goal-directed behavior' [10, page 186]. Similarly, a recent, though brief definition of executive function is that it is 'skills in the control used in the service of specific goals' [68, page 945]. Although somewhat vague, these show two important features, firstly, top-down control of other cognitive processes, and secondly, the importance of goal-directedness.

There are various classes of behavior that are not goal-directed, and consequently not usually under executive control, including innate motor reflexes such as eye-blinks to stimulation of the eyeball, defensive fixed reaction patterns, such as freezing, and conditioned fear responses [69]. Many types of cognitive response are not goal-directed, such as attending to our own name heard in background speech- the cocktail party phenomenon [70]. A particularly important class of non-goal-directed behaviors are instrumental actions that are habitual, which can be distinguished experimentally from goal-directed actions [71-76].

Expanding on this important distinction, from learning theory, it is known that instrumental conditioning proceeds from goal-directed control to automatic habitual responses [72]. A rat trained to press a lever for reinforcement will, during early trials, press the lever in order to achieve the reinforcer. This is known because devaluation of the reinforcer produces rapid extinction of responses. After multiple learning trials, even if the reinforcer is devalued, the subject continues to respond [77]. This procedure distinguishes goal-directed from habitual responding [74]. The distinction (goal-directed versus habit) is also known as model-based and model-free in computational reinforcement learning [73, 75], and as declarative and procedural memory in cognitive psychology and neuroscience [73]. The role of declarative memory is associated with representing the goal while also involving executive processes in action directed toward that goal [71]. Indeed, goal-directed instrumental learning (model-based learning) and executive cognitive control are thought to share a common set of processes [78].

Therefore, on approaching a situation that requires a response, people may use either goal-directed actions, that are controlled by the consequences, or habits, that are controlled by their antecedents. The neurological bases of these systems have been explored in humans and other species, and as would be expected, goal-directed action is cortically driven by the prefrontal and parietal regions and their subcortical loops [76]. When that brain system is damaged, a common clinical consequence is a reduction in goal-directed behavior [79], and such patients display 'goal neglect' [44].

Instrumental actions to achieve a goal, such as pressing a button to receive something wanted, seem rather simple. Nevertheless, they represent the basics of the top-down cognitive control of behavior which constitutes executive function. Analysis of single-cell recordings in the monkey brain, and imaging studies of the human brain, have revealed how complex tasks are broken down and processed as subgoals, leading to the highly complex, intelligent goal-directed behavior that is usually described as executive function [51]. Tim Shallice has expressly argued that the goal-directed instrumental behavior system is equivalent to his Supervisory Attentional System and the habit-based system equivalent to his schema-based Contention Scheduling System [23].

Goal-directed (executive) action is performed with a conscious component, but habitual, schema-based actions, driven by stimuli, are performed without awareness [24, 46, 76, 80]. Furthermore, in dealing with novel situations, actions are at first conscious, executive, and goal-directed, but become stimuli-driven habits if repeated several times [72, 76]. It is likely that the goal-directed action system is the more advanced, which has developed to allow more flexible behavior. It is likely that, from an evolutionary perspective, the development of goal-directed action represents 'a quantum jump in general intelligence above that exhibited by simple stimulus-response systems' [74, page 68]. The evolution of goal-directed action, as the basis of intelligence, has been described in humans and other vertebrates, and suggested as a principle that could be applied in robotics to allow flexible, intelligent behavior [81]. Accordingly, the concepts discussed here, of goal-directed behavior, underlying what is commonly known as executive function, can be readily applied to artificial intelligence. Baldassarre and Granato suggest that goal-directness is consistent with many classical definitions of artificial general intelligence and is necessary for cognitive flexibility [82].

Indeed, in classical approaches to formal AI, such as the General Problem Solver [83] and ACT [84] emphasis is placed on breaking down tasks into subgoals. This supports the implementation of means-end analysis, a classical approach to human and machine problem solving. The establishment of subgoals drives the performance of actions that shorten the distance to the final goal within the state space, although such actions do not directly seem to contribute to the achievement of the final goal. For example, if we need to move a heavy box, we may establish the subgoal of emptying it before moving it. But, obviously, emptying a box does not directly contribute to moving it. Executive functions are goal-directed, by definition. But is it correct to equate them with intelligence? This will be explored in the following section.

2.3 Are Executive Functions 'Intelligent'?

Some researchers have expressly linked goal-directed executive functions with intelligent behavior [18, 44, 51, 82]. Furthermore, as described above, executive function ability appears to predict a range of educational and occupational outcomes, perhaps even better than intelligence does. However, the concepts of executive control and intelligence originated in quite different fields, and have consequently tended to be treated separately. Executive function as a concept developed in cognitive science and neuropsychology, while cognitive control developed in neuroscience, and intelligence is a core topic of differential psychology. One of the reasons for this historical separation is that opinion in neuropsychology and behavioral neurology was that patients with damage to the frontal lobes showed a dysexecutive syndrome, but often without any apparent impairment of intelligence [26, 35, 38-40]. This dissociation seemed to confirm that executive function and intelligence relied on separate cognitive processes.

It is now known that the connection is in fact much closer than originally thought. The problem was that psychometric intelligence tests, as used in neuropsychology and neurology, tend to contain assessments that are insensitive to impairment [85]. However, the concept of general intelligence, often known as the *g* factor, is a somewhat different idea, and refers to some general feature shared by all cognitive processes [86]. It is revealed by the positive manifold of correlations- the observation that when a large sample of people complete a large set of cognitive tests, all test scores positively correlated with each other [87]. When frontal lobe damaged patients with dysexecutive syndromes were tested for general intelligence, impairments were apparent [44, 47].

Similarly, research in differential psychology usually uses factor analysis and related methods to study human cognitive architecture. Such methods have shown that variation in one aspect of executive functioning, working memory, is almost completely explained by variation in general intelligence [88] and when executive function is considered as a singular trait, it may be fully explained by general intelligence [89]. Furthermore, when this factor analytic approach is extended to patients with brain lesions, the patterns of damage causing reduced general intelligence are almost identical to those producing reduced single-trait executive function ability- the fronto-parietal system [90]. Accordingly, imaging studies of brain activation in healthy participants suggest a singular fronto-parietal system that is involved with general problem-solving activities associated with either general intelligence or executive functions [51, 52]. In summary, this body of research suggests that there may be no such thing as specific executive functions, independent of a domain-general intelligence.

Nevertheless, the direct measurement of general intelligence requires analysis of large data sets, and multiple cognitive tests to derive the *g* factor. It may be that what is being measured is the overlap of many different cognitive processes, including a domain-general process, such as working memory, as well as other more domain-specific executive processes- an approach to understanding the positive manifold known as process overlap theory [54]. Furthermore, measures of general intelligence based on single tests (as opposed to latent variables from factor analysis) are usually used in research outside of differential psychology. The most common of these tests are versions of Raven's Progressive Matrices [91, 92]. When such tests have been used in studies on neurological patients, they have confirmed that many tests of 'executive function' do not reveal any impaired performance beyond that explained by general intelligence [47]. However, that is not true of all executive function tests. There are some that appear to reveal impairments independently of loss of general intelligence. These tests appear to measure abilities such as motor response cancelation, verbal response suppression, multi-tasking, and verbal abstraction [47], as well as Stroop task performance [43], and cognitive estimation [93], amongst others. Therefore, these neuropsychological studies indicate some executive processes cannot be equivalent to general intelligence.

2.4 Is Executive Function Resource Limited?

An important aspect of executive function is that it may have limited capacity. Baddeley explicitly described the Central Executive of his Working Memory model as a 'limited capacity attentional system' [29, page 8], and Shallice described the Supervisory

Attentional System as being ‘a general purpose limited capacity mechanism’ [24, page 12]. Although it might see obvious that all brain processes are limited by available processing resources, be they cognitive or biological, executive processing does appear to be special in this respect. At least from a phenomenological perspective, processes involving interoception (such as monitoring one’s own body temperature) or exteroception (such as vision) do not involve any experience of effort, or suffer performance declines over time, in contrast, executive cognitive processes do [94]. These observations suggest that whatever processes underlie executive functions, they may be limited by available resources. However, we can think of these limitations in various ways, including from biological, psychological, and human-machine interaction perspectives.

The Biological Aspect of Resource Limits. Brains, whether human or not, are subject to evolutionary pressure. One of these pressures is to be only as proficient in the control of behavior as is necessary. Brains are ‘expensive’ organs which consume large amounts of the body’s oxygen: approximately 20%, despite being only about 2% of body mass [95]. Therefore, it could be that executive control is limited as a resource by the need to maintain a brain that is only as physiologically active as necessary. Physiological costs of neural activity can be measured by blood oxygen consumption. When people engage in cognitive task performance, as compared to being at rest, the absolute increase in blood oxygen use can be calculated through magnetic resonance brain imaging. Within brain areas linked to executive functioning, the increases in oxygen consumption are indeed quite large, up to 26% [96]. However, with increased cognitive load, the increase in oxygen use over the whole brain is only about 4% [97]. This increase is probably important, but would constitute less than 1% increase in overall body oxygen consumption, and so other reasons may limit our use of executive resources.

One of these may be that engagement of brain regions involved in executive control is typically associated with simultaneous deactivation of areas of the brain’s default mode network [98]. This system of interconnected brain regions, separate from the executive control regions, appears to become active whenever a person is at rest but awake [55, 56]. The fact that engagement of executive-related neural processes involves the disengagement of the default mode network, suggests that a cost of executive control may be to processing in that latter system. The default mode network is dynamically involved in ‘sense making’ that integrates incoming social information with existing schemas to produce models of situations over time [59]. It has been directly implicated [58] in the processing of a type of scheme proposed in a well-known AI and human cognition theory of procedural knowledge- script theory [99].

Related to this, the default mode network may be responsible for pre-planned, reflexive behaviors, as such it may produce impulsive behavior [55]. This would suggest that not only do the executive-linked brain regions and default mode network functionality antagonistic, but they also represent the distinction between executive function and routine or stimuli-driven actions, such as the Contention Scheduling aspect of the Supervisory Attentional System [23-27]. Goal-directed executive function may be resource limited because the default mode network requires interruption of goal-directed behavior so that it can continually develop and maintain procedural action schemas.

The Psychological Aspect of Resource Limits. The evidence for the Central Executive of working memory being limited came particularly from dual-task procedures in which research participants would perform memory tasks simultaneously with some other tasks. From the outset of the Working Memory model, dual-task performance that hindered reasoning ability, beyond that explicable by the cognitive load in the phonological store, was used to hypothesize a flexible 'limited capacity workspace' [12, page 57]. Chess playing, a highly executive skill, and production of random numbers are both impaired by a secondary task that use executive processes, suggesting that the executive control mechanism is resource limited [29].

Likewise, the Supervisory Attentional System, the other canonical model of executive functioning, was based partly on arguments from dual-task performance, particularly in the distinction between (executive) attentional control and routine action generation [24]. In fact, its development was based on analysis of hierarchies of control, drawing on computer science and cybernetics, to argue that only one action plan can be fully active at any one time. Accordingly, when multiple goals are pursued, the full activation of one plan will ultimately inhibit performance of other goal-directed systems [80]. The argument is that executive processes are limited and can only be directed to individual goals. Persisting with individual goal-directed processes therefore has costs as they prevent other processes from achieving their goals [94].

Human-Machine Interaction and Resource Limits. Limitations to memory capacity and processing are often responsible of the errors by machine/system operators. The so-called human error is incorrectly perceived as caused by an erroneous behavior of the operator, who is therefore made liable for the error. However, in reality, the error emerges from a mismatch between the computer interface with which the operator interacts and the physiological, hence normal, limitations of human processing capabilities. Using operators as scapegoats obscures the real responsibilities in industrial and transportation disasters. In most cases, poor system design is the actual source of the error.

Post-completion error is a very subtle kind of executive function error, which has been discovered and extensively investigated during the last thirty years. This kind of error occurs when a subsidiary task is not carried out because its execution is preceded by achievement of the goal. In fact, once a goal is achieved, working memory stores may be cleared, with a consequent loss of the information associated with the completed task. This is an essential memory process, called short-term memory closure, which makes the capacity-limited short-term memory stores ready to work on a new task. However, some of the lost information may be needed for the performance of the subsidiary task, which then cannot be executed. A typical example of post-completion error occurs where we forget our bank card after withdrawing cash from an ATM. Our goal is achieved when we collect the cash and, if the ATM is programmed to deliver cash before returning the card, then the card may be forgotten [19]. In this situation the post-completion error may be avoided by programming the ATM to return the card before delivering the cash.

This post-completion kind of error has been recently identified as the cause of several aviation accidents. A typical situation is engine maintenance. In fact, engine doors may be left unlocked after maintenance, because the goal is the completion of the maintenance work, whereas locking the door is a subsidiary task. Unfortunately, such a subsidiary task cannot be anticipated as in the case of the ATM. Thus, this instance of post-completion error cannot be prevented, but may be reduced by establishing strict executive protocols.

2.5 Current Challenges to Understand Executive Functions

The identification of a domain-general multiple demand system in the brain, that underlies general intelligence and top-down cognitive control [51, 52], has been a useful development. This system appears to be resource limited, in that greater task difficulty is associated with greater engagement within that neural system [52]. This seems to be a core part of executive function. However, several established clinical tests of executive function appear to be sensitive to cognitive impairment independently of changes in general intelligence [43, 47, 93] and many cognitive processes appear to involve top-down cognitive control, beyond those currently conceived as being the core executive processes of working memory, inhibition and switching (e.g., semantic control). A current challenge in cognitive sciences is the identification of processes, and cognitive tests, which define specific executive functions that are not simply measures of domain-general intelligence. If executive function assessment merely measure intelligence, the concept of executive function is effectively redundant.

One point which may be relevant is that intelligence tests appear to be tests of convergent thinking. This concept refers to cognitive processes that focus in on a single unique solution, the task at hand working to channel processing in the direction of that answer. This is contrasted with divergent thinking in which processing may search many different possible solutions, with usually no unique response considered correct [101]. Finding alternative uses for objects is a good example of divergent thinking, while deductive reasoning is a good example of convergent thinking. If we examine the components of common intelligence tests, such as the Weschler tests of intelligence, or Raven’s Progressive Matrices, we see that test items invariably define what are correct responses. This is supported by validity studies which indicate that IQ predicts convergent thinking ability, but not divergent thinking ability [102]. However, this is not necessarily true of common tests that are used to measure executive functions.

3 A Proposal

A separation between convergent thinking (which focuses in on singular problem solutions) and divergent thinking (which searches for multiple possible solutions) has been used in psychology since the 1950s [101]. The concept has been particularly applied to educational outcomes [103]. Convergent thinking ability has been associated with achievement in science and engineering [5], and divergent thinking with humanities and arts, as an example, when compared to demographically-matched controls, skilled musicians have been found to have better divergent thinking ability, which is associated with greater activation levels in the frontal lobes [104]. Interestingly, a large meta-analysis of divergent thinking ability has shown that it appears to have only a weak relationship with intelligence test performance [105], suggesting assessments of divergent thinking primarily measure something other than general intelligence.

A classic test of divergent thinking is the Alternative Uses Test, which requires participants to produce as many different uses for common objects as possible during a time limit [20]. Performance for identifying new uses for objects is often compared with production of multiple, but not varied, uses. The ability to produce many uses is considered to indicate creativity. Furthermore, the production of ideas for new uses appears to be closely related to executive function, as shown by relatively high correlations with performance on phonemic fluency, a common measure of executive function [106]. On the other hand, production of multiple non-creative uses is said to indicate fluent responding, but measure memory access rather than executive processes.

Although intelligence testing is closely linked to convergent, but not divergent thinking [102, 105], it is not simply the case that executive function assessments show the opposite pattern. In fact, most widely used assessments of executive functioning require convergent thinking too. We argue here that this may be one of the reasons why statistically, intelligence is closely related executive function [88, 89].

3.1 Divergent Process and Limited-resource Executive Control

Divergent executive processes appear to be sensitive to dual-tasking, which likely indicates the role of a resource-limited processor, such as the central executive. The performance of a secondary task impairs the identification of new uses of objects, but does not impair the production of multiple, non-creative uses [107]. As previously indicated, sensitivity to dual-tasking is consistent with the use of a resource-limited attention mechanism such as the Supervisory Attentional System [24] or the Central Executive of the Working Memory model [29, 31]. Divergent tasks produce greater brain activations than non-divergent control tasks, particularly in prefrontal regions [108] and the frontal lobes in general are more active in during divergent tasks in highly creative people compared to normal control participants [104]. The regions indicated are thought to be the core aspect of the systems underlying executive functions, in particular the resource-limited multiple-demand system [51], which becomes more active with increasing cognitive load [52]. Level of activation in these frontal lobe regions may be considered as a physiological marker of resource usage, as they typically increase their blood oxygenation substantially during increased load [96]. The resource limitation is often linked to working memory, which may be the core executive function, underlying resource-limited domain-general processing [88]. However, even when tasks are matched for cognitive load, divergent executive processes appear to produce more widespread activations of the frontal lobes than working memory task performance [109]. This suggests that divergent tasks not only substantially challenge domain-specific aspects of executive processes, such as a ‘central executive’, but also domain-specific executive processes. One likely candidate for this is semantic control, identified as being executive mechanisms that interact with semantic representations [110].

3.2 Divergent Executive Process and Neural Systems

If divergent thinking involves executive functions, it would be expected to activate the same brain networks as standard executive tasks do. This has been found using functional magnetic brain imaging, and it has also been shown that the interaction with the default mode network is important, suggesting that both executive and controlled activity of heuristic processing, such as schema or habitual modes of responding [111]. Although the default mode network is often considered to be a brain system that is anticorrelated with executive control, the deactivations are likely important features of cognitive processing and predict behavioral performance on executive tasks [112, 113] and some parts appear to be actively involved in executive-attentional control [57].

A recent meta-analysis of brain imaging studies of divergent thinking confirmed the involvement of executive and default mode brain networks, but also emphasized the involvement of the semantic control network [114]. Thus, the neural basis of divergent thinking appears to involve wider networks linked to goal-directed, top-down cognitive control, than those implicated in domain-general intelligence, such as the multiple demand system [51-53], specifically the cognitive control system and the default mode network. This suggests that executive tasks that incorporate divergent goals may involve a wider range of top-down cognitive control mechanisms than convergent tasks.

3.3 A Taxonomy of Executive Functions Based on Task Goals

From a practical perspective there is a need to recognize executive control mechanisms that do not substantially overlap with intelligence or the core domain-general process that supports it. That is, processes that fractionate from the domain-general core process. An obvious place to look would be at executive functions which involve divergent process.

Here we propose a taxonomy of executive functions based on the convergent-divergent distinction. The method by which cognitive performance is measured can be classified based on the goal that is given to the participant. For example, a participant may be told to recall a set of numbers or words, or to reorganize them and then recall them. In such cases there is a right answer, and any other response is considered incorrect. Examples of such tests are various short-term memory and complex span tasks [115]. Some tests require recognition of the correct meaning of words or phrases, such as in the Proverb Test, or logical deduction as in the Twenty Questions Test, or overcoming distraction to respond correctly, such in the Stroop Test [116]. Assessments such as those clearly invoke convergent processes- responses are either correct or incorrect.

In contrast, in some cognitive tests, participants are given open-ended goals. They may be told to produce as many exemplars as possible from large sets. Multiple such fluency tasks exist and are commonly used in neuropsychology, including phonemic, semantic, ideational, design and gesture [117]. The goal given to the research participant or patient is to produce as many different examples as possible, a divergent processing instruction. Similarly, some tests require participants to avoid any predictable patterns, such as random number generation [118] or to complete sentences with words that make no sense [13, 119]. Such task goals are not at all convergent, and appear to be better classified as divergent. Thus, many assessments of executive function can be classified based on the instructed goal requirement- as either divergent or convergent. This classification is shown in see Fig. 1**Error! Reference source not found.**. There is a third commonly used goal requirement of executive function tests. This is to not respond. This occurs in psychomotor tasks such as the Go/No-go task and may be recorded as errors (omissions or commissions), response times, or estimates of processing times related to response cancelation, such as in the Stop-signal task [120]. Related to this, though not explored as an executive control mechanism, is the deliberate delaying of simple response times. This is a task goal that severely slows performance [86], suggesting that it invokes attentional top-down control at the cost of automatic, habitual responding.

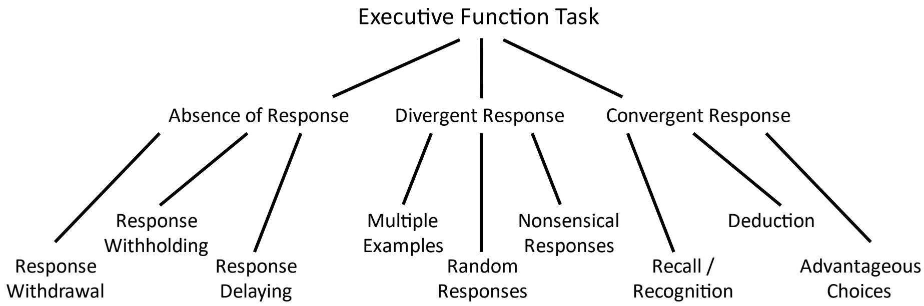

Fig. 1. An incomplete taxonomy of executive function tasks based on the goal of the task.

Convergent and divergent process, as defined here, can be independently impaired by brain damage [43]. In neuropsychological terms, they doubly dissociate, indicating their functional independence. Furthermore, executive function measures that are non-convergent may be better than convergent measures at predicting real-life intelligent performance, such as in the arts [104], academic achievement in high school [13] or university [6, 13], or predicting work-place performance such as in sales [18]. They therefore represent a relatively independent facet of intelligent behavior.

4 Conclusions

Executive functions, though originating in computer science, can be understood in terms of goal-directed behavior, a concept originating in psychology and neuroscience. Goal-directedness is a necessary component for both natural [74] and artificial intelligence [82]. Executive functions can also be considered as producing intelligent behavior. However, to provide some separation from the concept of psychometric intelligence, as it is customarily used, we also emphasize psychomotor inhibition and divergent cognition in the overall concept of executive processes. This point harks back to the first use of the term 'executive function' within psychology by J.P. Guildford, who also proposed the concept of divergent thinking [20]. Although speculative, the division of task types by goals, as shown in Fig. 1., could be applied in other areas to explore, and perhaps advance the understanding of top-down executive control of intelligent goal-directed action in the human sciences. Such an approach could also be applied in computer science to better understand the production of artificial general intelligence.

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