Retiring the central executive

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Abstract

Reasoning, problem solving, comprehension, learning and retrieval, inhibition, switching, updating, or multitasking are often referred to as higher cognition, thought to require control processes or the use of a central executive. However, the concept of an executive controller begs the question of what is controlling the controller and so on, leading to an infinite hierarchy of executives or 'homunculi'. In what is now a QJEP citation classic, Baddeley (1996) referred to the concept of a central executive in cognition as a 'conceptual ragbag' that acted as a placeholder umbrella term for aspects of cognition that are complex, were poorly understood at the time, and most likely involve several different cognitive functions working in concert. He suggested that with systematic empirical research, advances in understanding might progress sufficiently to allow the executive concept to be 'sacked'. This article offers an overview of the 1996 article and of some subsequent systematic research, and argues that after two decades of research, there is sufficient advance in understanding to suggest that executive control might arise from the interaction among multiple different functions in cognition that use different, but overlapping brain networks. The article concludes that the central executive concept might now be offered a dignified retirement.

Reasoning, problem solving, comprehension, learning and retrieval, inhibition, switching, updating, setting and maintaining goals, or multitasking are often referred to as higher cognition, thought to require control processes or executive functions. Each is associated with separate programmes of research that explore the empirical phenomena associated with these human abilities, and their theoretical underpinnings. One approach to integrating understanding across these different scientific endeavours is to consider the human cognitive architecture that supports these abilities: To explore whether cognitive functions that support reasoning might also be important for language comprehension, the ability to inhibit irrelevant information, to maintain goals, or to carry out multiple overlapping tasks. This was, and is a primary focus for understanding executive functions in the context of human working memory: The ability to maintain and update mental representations of rapid changes in our environment, to undertake ongoing mental processing, and to interact with the world on a moment to moment basis. A landmark paper in the understanding of executive functions in working memory was published by Baddeley (1996) in the Quarterly Journal of Experimental Psychology (QJEP), considered now a QJEP classic with over 2300 citations at the time of writing (Google Scholar, July 2015).

The importance and influence of the Baddeley (1996) paper is best understood by first considering the scientific context that was established 22 years earlier. Baddeley and Hitch (1974) described a series of experiments exploring the relationship between short-term verbal memory and what they and others (e.g. Atkinson & Shiffrin, 1968; Broadbent, 1958) referred to as control processes for everyday tasks such as learning and retrieval, language comprehension, and reasoning. Together, the temporary memory and control processes were considered by Baddeley and Hitch as components of a working memory system. During the following two decades, Baddeley and his colleagues focused on the characteristics of verbal short-term memory, which they viewed as comprising a phonological store and an articulatory rehearsal process. Subsequently these were referred to collectively as the articulatory loop (Baddeley, 1986) or phonological loop (Baddeley, 1992). There was less emphasis on the characteristics of short-term memory for visual or other non-verbal material, or on the control processes that Baddeley (1986) referred to as the central executive of working memory. In 1994, during the first international conference on working memory, in Cambridge, UK, Baddeley presented a series of studies that were directed at exploring the central executive concept in some detail, and these, along with other experiments were

reported in the Baddeley (1996) paper published in a special issue of QJEP, edited by Graham Hitch and myself.

The key finding in Baddeley and Hitch (1974) was that healthy adults can retain serial ordered sequences of three verbal items while they are undertaking demanding comprehension, reasoning, or free recall tasks, with no impact on the performance of serial verbal recall or of the concurrent task. Retaining an ordered sequence of six verbal items resulted in reduced performance of a concurrent demanding task, but the impact on performance was exactly the same regardless of the level of complexity of the concurrent reasoning, comprehension, or free recall task. Baddeley and Hitch (1974) argued that there is a short-term verbal memory system with a capacity of perhaps three or four items, that can function in parallel with the more complex processes of reasoning and language comprehension. However, when the capacity of that short-term verbal memory system is exceeded, then a control process such as mental verbal rehearsal is required. Reasoning and comprehension perhaps overlap with rehearsal of the letters or consolidation of the letters in memory, but do not overlap with short-term storage unless the memory load exceeds the capacity of the short-term storage system. That is, verbal short-term memory and control processes only partially rely on overlapping cognitive resources.

So, control processes function to support memory, but only when memory demands are high. However, this raises a major question as to the nature of those control processes; whether there is one flexible process that can support reasoning, language, problem solving, and creativity, or multiple such processes, each supporting a specific set of mental operations. Related questions spring to mind as to whether the control comes from previously learned and practiced cognitive skills and strategies, or from some overarching executive function that might be reflected in our conscious experience of controlling our mental and physical actions. The latter can lead to concerns about what is controlling the executive, what is controlling the controller, and so on, with the risk of having an infinite hierarchy of executive controllers or homunculi. The former avoids the homunculus problem but might be seen as too mechanistic, and begs the question as to how these control skills are acquired. How might control functions be implemented in the brain? Finally, as Baddeley himself noted, is the central executive concept essentially a convenient label or placeholder for all of the cognitive functions that are difficult to understand or explain: a conceptual ragbag?

Baddeley tackled the above, seemingly intractable, questions in his 1996 paper first by dismissing two potential approaches. The first of these was to draw on evidence linking impairments of control functions to damage in areas of the prefrontal cortex. This evidence, he argued, could tell us something about where in the brain control functions are implemented, but would tell us little or nothing about how those control functions are organised or implemented in cognition. Rather than define these impairments in terms of neuroanatomy (frontal deficits), Baddeley proposed the term 'dysexecutive syndrome' to refer to the cognitive functional impairments observed. A similar argument that questions the explanatory value of using neuroanatomical loci to define cognitive functions has been applied to the accumulated evidence from functional brain imaging studies of healthy adults (e.g. Page, 2006). Knowing which areas of the brain become more active when performing a cognitive task might tell us very little about precisely what that area of the brain is doing in order to support task performance. Increasingly, the evidence seems to indicate that communication between different brain areas is rather more important for supporting complex cognition than any one specific area (e.g. Nijboer, Borst, van Rijn, & Taatgen, 2014; for reviews see Charlton & Morris, 2015; Courtney, Roth & Sala, 2007; Nagel & Lindenberger, 2015).

The psychometric approach which attempted to link clusters of executive functions with measures of general intelligence, as well as with the frontal lobes was also viewed by Baddeley as unlikely to be fruitful. A range of studies available at the time and others published not long after the 1996 paper suggested that there were diverse executive functions that generated small positive intercorrelations, but they lacked the coherence that would be needed to support the concept of a unitary or general factor for executive functions (e.g. Duncan, Johnson, Swales & Freer, 1997; Duncan & Owen, 2000). This evidence indicated that multiple brain areas are involved in any one task, and that different brain networks might be deployed to meet the cognitive requirements of any given task. So, if researchers were to run a large battery of different tasks on a large number of healthy adults, then a factor analysis might yield a single factor that could be interpreted as a general mental ability. But that general ability might simply reflect the efficiency with which different brain areas communicate with one another, as well as the general health and efficiency of the areas that are communicating. It could be argued that this misses the possibility that different combinations of brain networks could underlie different task requirements. More on this topic later.

Baddeley's favoured approach was to retain the homunculus as a placeholder, and over time, to use experimental and neuropsychological approaches to identify, and split off individual functions that were part of the homunculus bundle of poorly understood aspects of higher level cognition. This was a long-term strategy, but seemed to offer a more systematic approach that would eventually lead to the demise of the homunculus and its replacement with empirically supported multiple cognitive systems, each with a different and specific set of functions. Achieving this goal would then characterise executive control as arising from the operation of and interaction among these multiple systems rather than assuming a single executive controller.

Identifying Control Processes

In an initial attempt to identify possible control processes that typically were viewed as executive functions, Baddeley (1996) explored the state of the science for concurrent performance of two tasks, switching retrieval strategies, selective attention and inhibition, and maintenance and manipulation in long-term memory. Although those were treated as four separate topics in the 1996 paper, the first three all come under the broad concept of attention, so I will consider them under that heading, then discuss the possible involvement of long-term memory, followed by a discussion of attempts to identify other possible executive functions.

Selective attention, dividing attention and dual task performance

Baddeley addressed the general concept of attention from several different perspectives, reflecting the view that attention tends to be a rather broad label for a range of different cognitive functions. One of these is the notion of spreading a limited capacity attention system across different, and possibly conflicting information and processes. A special case of this is the idea of dividing attention between two tasks, possibly with rapid switching between them. A second is the ability to switch attention between different retrieval strategies. Here, Baddeley focused on random generation of oral responses from a well-learned set such as the alphabet or a number range. A third is the ability to focus attention on one set of information or cognitive processes while inhibiting others. A fourth, not considered

in any detail by Baddeley or in the current article is the ability to maintain or sustain attention over a period of time. I will first consider each of the first three examples in turn.

Performing two tasks concurrently

Previous studies (Baddeley, Lewis, Eldridge & Thomson, 1984) had provided evidence that retrieval from long-term memory is largely automatic and unaffected by a concurrent attention demanding task. However, Baddeley argued that ensuring, for example, letters of the alphabet are output in a random order requires switching between retrieval strategies. It also requires inhibition of the tendency to use the well learned alphabetical order, and keeping track of the frequency with which individual letters or short letter sequences are generated to avoid having too many repetitions.

Doing two things at once is often described as dividing attention, a concept that assumes there is a single overall pool of attentional capacity that can be divided among a range of tasks being performed concurrently (e.g. Broadbent, 1958; Naveh-Benjamin, Guez, Hara, Brubaker, & Lowenschuss-Erlich, 2014; Pashler & Johnston, 1998). This assumption necessarily implies that each of the concurrent tasks receives only some of the attentional capacity, and therefore should generate poorer performance on each task than if all of that capacity were to be devoted to a single task. Before and since 1996, a large volume of research has demonstrated overall reductions in performance that arise from attempting two tasks at the same time, or that closely follow one another. However, for many of these studies, the research focus has been on bottlenecks during initial perception or encoding of two or more concurrent stimuli, or during the production of vocal or manual responses that compete for output (e.g. Naveh-Benjamin et al., 2014; Pashler, 1994). In these kinds of studies, attention refers to how the cognitive system interacts with the immediate environment, and to the limitations that arise when attempting to deal with multiple information sources and multiple possible actions. Often such studies place similar types of demands on cognition, such as both involving memory for words and numbers, or both involving visual presentation of stimuli and manual responses. Those kinds of tasks have been explored in the content of theories of selective attention, without specific reference to the Baddeley concept of working memory. Instead, Baddeley was referring to how the cognitive system handles the concurrent cognitive operations that are required for remembering and/or processing material that has already been encoded through perception,

where the task requirements are dissimilar, and where there is no, or minimal competition among possible responses. That is, the dual task cognitive requirements are not confounded by task similarity or input and output conflicts.

Baddeley (1996) referred to a series of experiments published 10 years earlier (Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986) in which healthy younger and older adults, and a group of individuals with Alzheimer's disease were asked to remember and repeat back strings of random digits while they were tracking a moving target on a computer screen. Conflicts during input of the stimuli and output of responses were avoided by using aural presentation of each digit sequence for oral serial recall, and using a visual display for the moving target which was tracked with a hand-held stylus. Crucially, each participant was first assessed for his or her ability to perform each task on its own. So, each person was asked to repeat back random lists of digits, with the lists gradually increasing in length. The longest sequence that a participant could recall successfully was taken as their maximum capacity, or span, for oral serial recall following auditory presentation. Next, each participant was asked to use a stylus to follow a small, randomly moving target around a computer screen. The speed of the target gradually increased, and the maximum speed at which a participant could keep the stylus on the target for around 70% of the time was taken as their maximum capacity, or span, for visuo-motor tracking. Finally, each participant was asked to follow the moving target at their own maximum speed while they listened to and orally recalled sequences of digits set at their own individual maximum sequence length.

The procedure of titrating, or adjusting the demand of each task performed on its own, and using the individually titrated demand in the dual task condition has two advantages. First, each participant acted as their own single task control against which to assess the impact of dual task requirements, rather than relative to a control group. Second, it allowed us to equate single task performance across groups, with the older healthy participants and the Alzheimer participants, as well as the younger healthy participants, all being asked to perform close to their individual limits on each task performed on its own. So, if any individual or group performed poorly in the dual task condition, we could check whether this was because of the dual task demand or because they also performed poorly in one or other of the single tasks. If we assume that there is a single maximum attentional capacity, then pushing each participant to their personal best (span) for recalling digits, or for following a moving target should use most or all of that capacity within each single task condition. If we then ask

people to perform two tasks, both of which are set at individually titrated maximum demand levels, then we might expect a very substantial reduction in overall performance when both tasks are performed concurrently. Results were rather surprising for the assumptions of divided attention. Far from the catastrophic reduction in performance under conditions of performing two very demanding tasks concurrently, the dual task performance levels for the healthy adults were around 80% to 85% of the single task performance for both tasks, and this did not differ between the younger and older participants. This suggested that the performance cost is very small when doing two very demanding but dissimilar tasks concurrently compared with performing each task on its own, as long as we avoid input and output bottlenecks. Moreover, older adults showed no age-related impact specifically of dual task performance. Younger and older healthy participants showed the same very modest cost to performance under dual task conditions. This is despite well established findings that older people perform more poorly than younger people on a very wide range of cognitive tasks (see reviews in Perfect & Maylor, 2000).

Even more intriguing, is that the Alzheimer participants in the Baddeley et al. (1986) study showed a drop of around 40% in dual task performance compared with their own single task performance. This pointed to a specific dual task impairment in Alzheimer's disease that was not present in healthy older people. The fact that such a specific impairment could be detected in the Alzheimer group suggests that in healthy people, performing two tasks concurrently may reflect a specific ability that is not affected by healthy ageing, but is affected by Alzheimer's disease. Moreover, given the extensive evidence that older healthy people show clear reductions in attentional capacity, and specifically in the ability to divide attention (for a review see Kilb & Naveh-Benjamin, 2015), the lack of an age-related dual-task impairment reported by Baddeley et al. (1986), suggests that the particular task combination that they used did not place a heavy load on a limited attentional capacity. The original findings reported by Baddeley et al., (1986) were replicated and extended multiple times over the following thirty years (e.g. Cocchini, Logie, Della Sala & MacPherson, 2003; Della Sala, Cocchini, Logie & MacPherson, 2010; Foley, Cocchini, Logie & Della Sala, 2015; Logie, Cocchini, Baddeley & Della Sala, 2004; MacPherson, Della Sala, Logie & Wilcock, 2007; Ramsden, Kinsella, Ong & Storey, 2008; Sebastian, Menor and Elosua, 2006) while addressing potential criticisms of its interpretation, such as the argument that dual task is more difficult than single task for someone with a damaged brain. As noted by Baddeley (1996), if the results for the Alzheimer patients were just due to overall

task difficulty, then we would have expected to see an effect in the healthy older participants who generally achieve poorer cognitive performance than younger people with equivalent educational levels. However, the older and younger groups did not differ in dual task cost.

Logie et al., (2004) tackled the difficulty criticism more directly by following the general procedure from Baddeley et al. (1986), but in the dual task condition one or other of the tasks varied systematically in demand from below individual capacity through measured capacity to a demand that was greater than measured capacity. When digit sequence length was fixed and tracking speed increased, the tracking performance dropped, but digit recall was completely unaffected in healthy younger and older adults as well as for Alzheimer participants. When tracking speed was fixed and the digit sequence length was increased, digit recall declined, but tracking performance was unaffected in all three groups. As in the Baddeley et al. (1986) study there was a small overall impact of dual task versus single task in the healthy adults, and much larger overall dual task impairment in the Alzheimer group, but the dual task cost did not vary as a function of task difficulty for the patients or the healthy controls. That is, the Alzheimer patients had a specific problem performing two tasks at the same time, regardless of how easy or difficult was each individual task. Likewise, the performance of the healthy older and younger controls was insensitive to overall dual task difficulty.These findings are consistent with the Baddeley and Hitch (1974) result described earlier showing an insensitivity to increasing load when combining a memory preload with a concurrent demanding task in healthy young adults.

More recently, similar results have been found for temporary visual feature binding tasks. In these tasks, participants are presented briefly with a small array of colours, of shapes, or of colour-shape combinations. After a blank interval, a second array is shown, but with changes in one of the colours, or one of the shapes, or with two of the shapes swapping colours (e.g. Allen, Baddeley & Hitch, 2006; Colzato, Raffone & Hommel, 2006; Logie, Brockmole & Vandenbroucke, 2009; Treisman, 2006). A range of studies has demonstrated that this kind of task is insensitive to cognitive changes in healthy ageing (Brockmole & Logie, 2013; Brockmole, Parra, Della Sala & Logie, 2008; Brown & Brockmole, 2010; Isella, Molteni, Mapelli, and Ferrarese, 2015; Rhodes, Parra & Logie, in press). Older healthy people show no greater drop in performance than do younger healthy people when detecting changes in colour alone or shape alone, compared with detecting changes in colour-shape combinations. However, people with Alzheimer's disease show a very much larger drop than younger and

older healthy people in temporary memory for binding, compared with memory for shapes alone or colours alone (Parra, Abrahams, Fabi, Logie, Luzzi & Della Sala, 2009; Parra, Abrahams, Logie, Mendez, Lopera & Della Sala, 2010). That is, Alzheimer's disease, but not healthy ageing, appears to be associated with a specific impairment in the ability to remember arbitrary combinations of colour and shape on a temporary basis, pointing to what might be considered an executive 'temporary binding' of two different kinds of information. This set of findings complements Baddeley's discussion about a control function that might be difficult to detect in healthy adults, but becomes apparent as a specific impairment in Alzheimer's disease.

At a cognitive level, the results described above identified at least one specific control function for dual task performance, and a possibly related function for temporary binding of colours and shapes. However, they leave a range of unanswered questions as to how this control function is implemented without an homunculus acting as a dual task coordinator or binding mechanism. One possible hypothesis is that when healthy adults perform two tasks that have very different cognitive and input/output requirements, then each task deploys a different brain network, and these networks can operate largely in parallel. For example, serial ordered oral recall of digit sequences has been shown to involve areas in the left hemisphere, including the inferior parietal gyrus, the inferior frontal gyrus, middle frontal gyrus and deep white matter structures in the frontal region (Logie, Venneri, Della Sala, Redpath & Marshall, 2003; Paulesu, Frith & Frakowiak, 1993). In contrast, visuo-motor tracking has been shown to involve left precentral and postcentral gyri, bilateral superior parietal lobules as well as the supplementary motor area, cerebellum, thalamus and hippocampus (e.g. Nijboer et al., 2014). Nijboer et al. (2014) asked participants to perform an n-back task, a tracking task and a tone-counting task, as single tasks and also as pairs of tasks concurrently. They demonstrated that when performing two concurrent tasks, the reduction in performance is closely related to the extent to which there is an overlap in the brain areas that are activated when performing each task on its own. When brain areas overlapped, as in the combination of n-back and tracking, there were clear reductions in performance under dual task compared with single task conditions. When there was little or no overlap in brain areas, as for tone counting and tracking, there was little or no reduction in performance when performing the two tasks concurrently compared with performing each task on its own. There appeared to be no evidence for an area of the brain specifically associated with a 'dual task executive controller'. Rather, the cognitive performance under dual task conditions arose

from how the brain networks interacted, and the extent to which they overlapped. Analogous findings have been reported for feature binding, with different, but partially overlapping areas of activation used for temporary memory for respectively colour and for shape, but with both areas activated together with additional prefrontal cortical areas when remembering colour-shape combinations (Parra, Della Sala, Logie, & Morcom, 2014).

The early stages of Alzheimer's disease are known to damage brain white matter that provides neural connectivity between brain areas, particularly the white matter tracts between the anterior and posterior brain areas (e.g. Bokde, Ewers & Hampel, 2009). The amount of damage to white matter observed in Alzheimer's disease is substantially greater than the gradual change in white matter that occurs in healthy ageing (Charlton & Morris, 2015). So, even if an individual network can still function, if connectivity with other brain areas is compromised then performance that relies on that connectivity will suffer. This offers a plausible account for the specific dual task impairment in Alzheimer's disease with task combinations that show very little dual task cost in healthy younger and older participants. It also offers a plausible account for the specific feature binding deficit associated with the disease. Moreover, these findings may have broader clinical impact in pointing towards the possible use of dual task and binding paradigms to develop cognitive assessments that are specific for aiding the detection and monitoring of Alzheimer's disease (Logie, Parra & Della Sala, 2015).

The role of long-term memory

Random generation
Baddeley (1996) discussed two approaches to addressing the contribution to executive control functions from the lifetime of stored episodes, and of acquired knowledge and skills. One of these considered executive control of retrieval strategies through the use of random generation; the technique of asking participants to randomly generate items from well learned sets such as the alphabet or the numbers between 1 and 10. The other considered the possibility that working memory largely comprises activated long-term memory coupled with a focus of attention.

Regarding retrieval strategies, a previous set of studies by Baddeley et al. (1984), provided evidence that retrieval of well known and well learned facts from long-term memory is

largely automatic and unaffected by a concurrent attention demanding task. Baddeley argued that successful random output of items from a well learned set such as the alphabet requires switching between retrieval strategies. It also requires inhibition of the tendency to use the well learned alphabetical order, and requires the participant to keep track of the frequency with which individual letters or short letter sequences are generated to avoid having too many repetitions. Together, the requirement to switch retrieval strategies and to inhibit familiar sequences and repetitions were expected to disrupt retrieval from long-term memory. This proved to be the case, given that random generation disrupted the ability to generate examples of items from specific categories, such as fruit or animals, and affected scores on a standard test of fluid intelligence (Baddeley, Emslie, Kolodny & Duncan, 1998). Other studies showed that random generation disrupted simple counting of dots on a screen (Logie & Baddeley, 1987), syllogistic reasoning (Gilhooly, Logie, Wetherick & Wynn, 1993), and mental arithmetic (Logie, Gilhooly & Wynn, 1994), consistent with Baddeley's argument that random generation could be considered a task requiring executive control processes.

The subsequent use of random generation varied between its role as a secondary task to investigate the effect of possible disruption of complex primary tasks, and the understanding of the random generation task itself. The use of the task was also complicated by the labour-intensive scoring required of audio-recordings of lengthy orally generated sequences from each participant. One attempt to avoid this scoring problem involved random keypressing of a set of keys that allowed automated recording and scoring of responses. However, that approach removed the requirement to retrieve items from well-learned sets in long-term memory. An ingenious alternative was explored by Vandierendonck, De Vooght, and Goten (1998) who asked participants to generate random time intervals between taps on a single key. This allowed for automated recording and scoring, and also avoided the need to generate oral responses or spatially separated movements. It offered a purer measure of the processes involved in inhibiting the repetition of sequences of inter-tap intervals of the same length. However, it also removed the requirement to retrieve items from long-term memory or to switch retrieval strategies. Although random interval tapping appeared to show some promise, it was rarely used in subsequent research.

More recent studies have attempted to develop computational models of random generation, but these attempts run into the problem that oral random generation involves a range of cognitive functions. For example, Sexton and Cooper (2014) developed one model, but in so

doing, came to the conclusion that random generation involves a range of different functions, each of which has to be incorporated in the model. This highlights a further issue about what precisely is meant by the term 'executive function'. In the case of random generation, this might simply refer to the complexity of the requirement to deploy a range of different cognitive functions in concert to comply with task instructions. So, again, the notion of an executive might arise from the need for different functions to interact rather than referring to an overarching control mechanism.

Activated long-term memory

Here, Baddeley (1996) first briefly considered that people with dense amnesia show a broadly intact ability to recall material presented just a few seconds previously, and an ability to perform logical memory tests as well as to hold conversations. Yet, such individuals can remember little or nothing about those experiences when tested just 30 minutes later (Baddeley & Wilson, 2002; Wilson & Baddeley, 1988). It appeared that the executive abilities to activate previously learned skills and knowledge for language and logical reasoning as well as for comprehension and remembering short prose passages or an ongoing conversation was largely intact, but the ability to store that information over longer periods and retrieve it subsequently was severely impaired. Baddeley (1996) interpreted the intact functions as demonstrating intact executive involvement in temporary activation of long-term memory. He also recognised that even the so-called 'slave system' or domain-specific temporary verbal memory store, the phonological loop, requires access to the lifetime of acquired knowledge about phonology. How else could there be evidence for phonologically based errors when recalling visually presented word sequences or letter sequences (e.g. Conrad, 1964)? So, the operation of the Baddeley and Hitch (1974) working memory and its subsequent updates (Baddeley, 1986; 2000; 2007; 2012) clearly requires an interaction with long-term stored knowledge.

In Baddeley (2000), there is the proposal of an extra component of working memory, referred to as the episodic buffer. This component is thought to support the binding of information from other working memory components and from long-term memory into a temporary but coherent and limited set of information chunks representing the current event. In amnesic patients, the episodic buffer is thought to be intact, reflected in largely normal executive functioning, coupled with severely impaired ability to recall material after a delay. In healthy

individuals, most retrieval from long-term memory is thought to be relatively automatic, and the episodic buffer provides an interface between working memory and long-term memory viewed as two separate systems.

Logie (1995, 2003; 2011) proposed an alternative view for the relationship between long-term memory and working memory by proposing that incoming stimuli activate representations in long-term memory and that the product of those activations are transferred to multiple components in working memory. These components include a temporary visual buffer referred to as the visual cache, and a buffer for retaining movement sequences referred to as the inner scribe, as well as the components of the phonological loop, and the operation of a range of executive functions. The buffers and executive components of working memory then act together with activated long-term memory to support task performance, rather than support coming from a single memory system. Evidence for this view came from, for example, selective impairments in neuropsychological patients (Vallar & Shallice, 1990; Logie & Della Sala, 2005), domain specific interference effects in dual-task studies of healthy individuals, including the Baddeley et al. (1986) and Logie et al. (2004) studies mentioned earlier, and, more recently, studies of visual and phonological codes in serial recall tasks (Saito Logie, Morita & Law, 2008; Logie, Saito, Morita, Varma & Norris, in press).

Other researchers have argued that working memory is not a separate system that interacts with long-term memory, but is essentially currently activated long-term memory (e.g. Cowan, 1995; 1999; 2005; Crowder, 1993; Ericsson & Kintsch, 1995). For example, Ericsson and Kintsch (1995), referred to 'long-term working memory' to account for the ability of experts to hold in mind a great deal more information about their areas of expertise than would be expected from a limited capacity working memory. This has been demonstrated in a wide range of areas of expertise, notably in chess players (e.g. de Groot, 1965; Saariluoma, 1990) and in expert restaurant serving staff (Ericsson, & Polson, 1988). Ericsson, Chase, and Falloon (1980) reported a notable single case of an individual (Falloon) who learned to repeat back random sequences of up to 80 digits. Other researchers have shown similar superior working memory performance in experts in soccer being asked to remember sets of scores from soccer matches (Morris, Tweedy & Gruneberg, 1985). Even residential burglars show superior visual working memory for burglary-related details in photographs of houses (Logie, Wright & Decker, 1992; Wright, Logie & Decker, 1995). However, a common theme across these studies is that the participants showed normal levels of working memory performance

when asked to recall details that could not be supported by their specific expertise, such as when chess experts are asked to recall positions of pieces placed randomly on the board, when soccer experts are asked to remember random scores rather than scores from actual games, and when burglars try to remember details of interest to house buyers such as the decoration of the doors. That is, knowledge and learned strategies retrieved from long-term memory can be used to generate high levels of memory performance within an individual's areas of expertise. When performing tasks that cannot use these forms of expertise, memory performance is at the level expected from a limited capacity working memory system. Ericsson and Delaney (1999) recognised the need to maintain the concept of a short-term working memory to remember novel details for short periods of time, complementing their concept of long-term working memory contributing to overall memory performance by drawing on acquired expertise.

Cowan (1995; 1999; 2005) developed the idea of working memory as activated long-term memory, but added the idea of a limited capacity focus of attention on a small area of what is currently activated. This combination of activated long-term memory has been referred to as the 'embedded processes model' (Cowan, 1999). The focus of attention could be equated to an executive function for selective attention to a section of the current contents of activated long-term memory or of the current contents of consciousness (for a recent discussion see Logie & Cowan, 2015). Cowan has reported substantial evidence for the notion of a focus of attention that can support temporary memory for 3 or 4 items at any one time (e.g. Chen & Cowan, 2005; Cowan, Chen & Rouder, 2004). However, precisely what controls the focus of attention in Cowan's model is not entirely clear, and leaves open the homunculus question. Although Cowan argued primarily for this 'unitary' view of memory, rather than a working memory system that is separate from long-term memory, subsequently (Cowan, Saults & Blume, 2014) acknowledged that there appeared to be peripheral systems, notably the phonological loop, that could support verbal rehearsal without drawing heavily on the limited capacity focus of attention. This is compatible with the phonological loop in the Baddeley model. However, Cowan views the focus of attention as the core of working memory function that allows for inhibition of currently irrelevant information as well as controlling which limited set of information is immediately available and relevant for the current task.

Individual differences and executive functions

While Baddeley and colleagues were developing the concept of executive functions using primarily experimental and neuropsychological approaches, an alternative approach was developed in parallel that viewed working memory as reflecting differences between individuals in their general mental capacity. Daneman and Carpenter (1980) devised a task which involved reading (i.e. language processing) a series of sentences and then recalling the final word of each sentence. The measure of performance was based on the maximum number of sentences that could be processed while successfully recalling all of the final words in the order of presentation. Daneman and Carpenter and their colleagues demonstrated that people who were good at this task also were good at a wide range of other complex tasks, such as language comprehension. Likewise, people who were poor at the task also were poor at language comprehension. The researchers argued that their task was measuring a fundamental human mental ability that they referred to as working memory, and the task was referred to as a working memory span task.

Subsequent studies developed different variations of the working memory span task. Most notably, Engle and colleagues (e.g., Engle, Kane, & Tuholski, 1999; Turner & Engle, 1989) developed a version that they called 'operation span', in which people were given simple arithmetic sums, instead of sentences, followed in each case by an unrelated word. Variation in how many words people could remember when interspersed with arithmetic showed good correlations with performance on language comprehension, but also on a wide range of other tests of cognitive ability, including general intelligence and performance in exams. Engle et al. (1999) emphasised that the operation span task was a measure not only of memory, but rather was a measure of the capacity to control attention when memory is required along with interference or distraction. This led Kane and Engle (2002) to refer to the concept of 'executive attention' which they viewed as the ability to inhibit distracting information. More recently, Shipstead, Harrison and Engle (2015) referred to working memory as the interaction between attention and memory.

Individual differences in working memory span task scores have been very successful in predicting performance on a wide range of mentally challenging tasks, including measures of fluid intelligence (e.g. Engle, Tuholski, Laughlin & Conway, 1999; Hicks, Harrison & Engle, 2015). However, there is accumulating evidence that working memory span tasks might not actually be ideal measures of working memory. Cantor and Engle (1993) argued that performance on the operation span task might reflect how much information could be activated from long-term memory at any one time. The working memory element was then

the ability to inhibit the impact of distraction, and to avoid an impact on memory from the intervening processing tasks. So, individuals with high operation spans are able to activate more information and are more effective at inhibiting distraction than are those with low operation spans. In this sense the ability to inhibit distraction is akin to one of Baddeley's executive functions, but Engle and colleagues view the memory measure in working memory span tasks as activated long-term memory. This view was reinforced in later studies by Unsworth and Engle (e.g. 2007). Further evidence that working memory span tasks might be measuring activated long-term memory rather than working memory was reported by Kane, Conway, Miura and Colflesh (2007) who demonstrated that individual differences in working memory span show low correlations with a widely used measure of working memory function known as the n-back task. In this task, participants are shown a series of items and are asked to decide if the currently presented item is the same as an item shown 1, 2, 3 or more items previously. As the stimulus list progresses, participants have to update their memory for the item that was 'n-back' in the series. So, n-back tests are thought to measure the capacity for rapidly updating the contents of working memory. The poor correlation between n-back scores and working memory span scores suggest that these two tasks are unlikely to be measuring the same cognitive functions. So, either there are at least two different functions of working memory - updating for n-back and inhibition of distraction for working memory span - or one of these tasks is not measuring a single attentional control function.

A further reason for thinking that working memory span tasks might not be ideal for measuring working memory is that the vast majority of studies that use these tasks score and report only the number of items recalled. As noted above, the memory demands of the task are increasingly viewed as reflecting storage through temporary activation of long-term memory representations of the items to be remembered rather than in a temporary buffer within working memory such as the phonological loop. Few studies in this area report performance on the processing element of the task which might offer a more direct measure of the 'working' or executive functions of working memory. One of the few exceptions was a study by Waters and Caplan (1996) who adapted a task originally described by Baddeley, Logie, Nimmo-Smith, and Brereton (1985) in which participants verified (rather than only read) a series of simple sentences and were asked to remember the final word of each sentence. Crucially, Waters and Caplan measured performance on the verification (processing) element of the task as well as recall performance. If processing and memory

both rely on the same limited capacity resource, then high levels of memory performance should result in low levels of processing performance and vice versa. So, we would expect large negative correlations between processing and memory performance in a working memory span task for list lengths that are close to maximum working memory capacity. In contrast, they found low to moderate positive correlations between processing and storage measures at all list lengths, not all of which were significant. When they generated a composite score that included both processing and memory performance, this yielded a correlation with other measures of high level cognition that was nearly double that obtained from the memory score alone. Similar patterns of poor correlations between processing and memory in working memory span tasks were reported by Daneman and Hannon (2007), and by Logie and Duff (2007), indicating that processing and memory in working memory span tasks make independent contributions to the variance that overlaps with general cognitive ability. Further studies by Duff and Logie (1999; 2001) demonstrated that performing a working memory span task that involves both processing and temporary memory results in very little overall reduction in performance compared with performing the processing task on its own or the memory task on its own. This suggests that processing and memory reflect largely independent, not interdependent cognitive functions. It is a conclusion that is compatible with Unsworth and Engle's (2007) view that memory in a working memory span task might reflect secondary, or long-term memory activation whereas the inhibition of distraction is akin to an executive function of working memory. However, it remains puzzling that in studies of individual differences in working memory span, there is rarely consideration of measuring performance on the processing elements of the task, yet it is the processing elements that might reflect executive functions in working memory.

Miyake, Friedman, Emerson, Witzki, Howerter, and Wager (2000) used the individual differences approach with a large battery of cognitive assessessments and a latent variable analysis to investigate whether a single factor or multiple factors might account for executive function in working memory. They identified three separate executive functions: inhibition of automatic responses, updating of representations in working memory, and the ability to switch between tasks or mental representations. They also acknowledged that there was evidence for a function that might support the ability to carry out two tasks concurrently. In a follow up individual differences study of a large cohort of twins, Friedman, Miyake, Young, DeFries, Corley, & Hewitt (2008) offered evidence for a genetic basis for individual differences in each of the executive functions identified in the Miyake et al. (2000) study.

Other studies have demonstrated that working memory functions appear to decline at different rates across the adult lifespan (e.g. Johnson, Logie & Brockmole, 2010; Kievet, Davis, Mitchell, Taylor, Duncan, Cam-CAN Research Team & Henson, 2014; Park, Lautenschlager, Hedden, Davidson, Smith & Smith, 2002; Park & Reuter-Lorenz, 2009), and this is compatible with the view that there are multiple specialised functions that are differentially sensitive to age. So, the idea that there are multiple functions that previously might have been considered to be supported by an executive homunculus, is being replaced by multiple cognitive processes, each of which serves a specific function, with performance perhaps constrained by the effectiveness of neural communication. So, the homunculus could be considered an emergent property of how different brain networks interact and are deployed to meet task requirements, as suggested by the Nijboer et al. (2014) and Parra et al. (2014) studies discussed earlier.

The arguments above could suggest that it is time for the concept of a single executive to be retired, and for us to consider that cognition could comprise a collection of multiple specialised skills, strategies and abilities that interact and act together as a self-organising system that does not require a central controller. There are certainly many examples of complex systems such as insect colonies that function very effectively with multiple specialised groups of individuals whose activities are controlled by the specialised functions within each group and by inter-group interactions rather than by a central executive controller. A range of computational models demonstrating executive control within self-organising systems (e.g. Barnard, 1999; Willshaw, 2006) have been proposed but this kind of computational modelling has yet to be fully developed as an alternative approach to understanding executive control within the human brain.

Conclusion

Baddeley (1996) asked whether it would be reasonable to remove the homunculus or central executive as a theoretical place holder. He concluded that there appeared to be a limited evidence base to do so at that time, and recommended a long-term empirical strategy of attempting to identify and understand executive functions. In the following two decades, considerable progress has been made in the identification of cognition functions that were in the bailiwick of the homunculus. So, is it ready to retire? There is not scope here to offer a comprehensive review of 20 years of research on the topic, and detailed reviews are available elsewhere (e.g. Baddeley, 2007; 2012; Baddeley & Logie, 1999; Logie, 2015; Logie &

Morris, 2015; Logie & Niven, 2012). In this article, I have highlighted some of the research suggesting that communication between different cognitive functions could be identified as crucial for successful dual task performance and for successful temporary feature binding. Evidence from structural and functional brain imaging appears to support this interpretation. Selection and implementation of retrieval strategies appears to be a second form of executive process. Research on individual differences in working memory has identified three others, namely inhibition of distraction, updating, and task switching.

So, if we can consider offering a dignified retirement to the homunculus with thanks for its function as a placeholder, can we also dismiss the idea of a single, general, limited capacity, but flexible attention system that remains a core feature of several, influential contemporary views of working memory (e.g. Cowan et al., 2014; Barrouillet & Camos, 2015; Hicks et al., 2015). Maybe we don't have to, if we return to the concept of self-organising systems, and the kinds of research questions that each approach attempts to address (Logie, 2011; 2015). If the entymologist is interested in the overall capacity and performance of an insect colony, then the colony might be viewed and assessed as a single, complex entity that is successful or otherwise in surviving within its environment. The overall performance of different colonies can then be compared to assess their different levels of success in survival. If instead, the interest is in the structure of insect colonies, the functions of its different groups, and how those individual groups contribute to the overall performance of the colony, then the concept of a single complex entity is much less useful. So too, if the primary research questions concern the maximum mental capacity of an individual for performing relative to other individuals in research tasks or in life success, then viewing executive functions as reflecting a single, flexible, limited capacity attention system is extremely useful. If, instead, the focus of the research is on understanding how the overall capacity is achieved, and on the structure and function of working memory, even when it is not operating at maximum capacity (as commonly is the case in everyday life), then the accumulated evidence points to multiple specialised functions that can operate in concert to give the impression that there is a single entity that supports on-line cognition.

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