Commentary of the book "After Phrenology"

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Michael L. Anderson

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Becoming an expert: Ontogeny of expertise as an example of neural reuse

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Abstract

In this commentary, we discuss an important pattern of results in the literature on the neural basis of expertise: (a) decrease of cerebral activation at the beginning of acquisition of expertise and (b) functional cerebral reorganization, as a consequence of years of practice. We show how these two results can be integrated with the neural reuse framework.

In *After Phrenology,* Anderson presented the *neural reuse* framework, which opposes both modular and holistic views of brain architecture. In evolutionary terms, neural reuse claims that the brain evolves, not by adding new specialized modules, but by acquiring new functions by re-combining local areas in new ways. Ontogenetically, neural reuse involves the processes of *interactive differentiation* (local areas have different profiles and interact in different ways as a function of development) and *neural search* (the active testing of multiple neuronal combinations until finding the most appropriate one for a specific skill, i.e., the neural niche of that skill).

One testable hypothesis of the neural reuse framework is that novices in a domain of expertise would show wide-spread brain activation when performing a domain-specific task, whereas experts would show a more focused pattern of brain activity. This is because, at the beginning of acquiring a skill, the brain is searching for an appropriate combination of areas, whereas the experts' brain has already settled in a specific network of brain areas to perform domain-specific tasks. Indeed, Anderson (2014) presents data supporting this hypothesis (e.g., Merabet et al., 2008; Petersen, van Mier, Fiez, & Raichle, 1998; Petersson, Elfgren, & Ingvar, 1997; Poldrack, Desmond, Glover, & Gabrieli, 1998).

The field of research on the neural implementation of expertise has been very prolific in the last 15 years; therefore, it seems pertinent to evaluate Anderson's hypothesis exhaustively in light of new data. In fact, Guida, Gobet, Tardieu and Nicolas (2012; see also Guida, Gobet, & Nicolas, 2013) reviewed the literature on neural implementation of expertise in tasks related to working memory. They found two effects: (a) studies investigating individuals who receive training in working memory-related tasks (from 2 hours up to 5 weeks) show mainly a decrease of cerebral activity in prefrontal and parietal working memory areas after training,

while (b) studies using experts and novices in different fields performing domain-specific working memory-related tasks tend to show that the brain areas activated to perform those tasks differ between novices and experts (Guida et al., 2012, referred to this effect as *functional neural reorganization*). As suggested by Anderson (2014), the first effect (i.e., the reduction of brain activity due to a number of hours of training) is consistent with the process of neural search. Even though the second effect was not envisaged by Anderson (2014), we propose that it is also compatible with neural search. The first effect reflects the fact that a developed skill finds a neural niche within the network of brain areas used at the beginning of skill acquisition, whereas functional neural reorganization reflects a more radical type of neural search: the skill finds its neural niche in a different set of brain areas. In the rest of this commentary, we explain in more detail these two effects, which are connected by Guida and colleagues in a two-stage framework, and link them to the three implications of the neural reuse framework that Anderson (2015) put forward in his précis (p. 2).

Experts: Re-using the mediotemporal lobe. *1) "First and most obvious, newly acquired capacities are generally supported by mixing and matching the same neural elements in new ways."* This first implication is in accordance with the expertise literature. As a consequence of their extended practice, experts develop domain-specific knowledge structures (i.e., chunks and more sophisticated knowledge structures; see an explanation in the next section). These new knowledge structures allow experts to re-use the mediotemporal lobe in a completely different way compared to novices (Campitelli, Gobet, Head, Buckley & Parker, 2007; Guida et al., 2012, 2013). While novices typically use episodic long-term memory areas (e.g., the mediotemporal lobe) for performing long-term memory tasks, experts are able to (re)use these areas also for performing working memory tasks.

As theorized by Ericsson and Kintsch (1995) and Gobet and Simon (1996), this occurs when there is a tight connection between working memory and long-term memory through retrieval cues or slotted schemas, which allow a fast transfer of information between these two types of memory (see also Gobet, 2000a, 2000b). Therefore, the interaction between working memory and long-term memory is crucial for functional neural reorganization to take place. This certainly echoes Anderson's (2014, p.40) view that "function depends much more on the *interactions between* parts than on the *actions of* parts," and relates to Anderson's (2014, p. 296) second principle of a functionalist neuroscience: "our complex and diverse behavioral repertoire is supported primarily by the brain's ability to dynamically establish multiple different functional coalitions."

The relation between working memory and episodic long-term memory also relates to another interesting effect described by Anderson: unmasking. The basic idea is that brain regions are supposed to be specialized to process one type of input (e.g., the occipital cortex is supposed to be specialized in processing visual input). However, under special conditions in which the source of dominant input is disrupted (e.g., injury, sensory deprivation), this brain area can process a different type of input, unmasking a new processing capacity for this area. Moreover, Anderson argues that the disruption of normal input is not a necessary condition, and that unmasking can be observed also under more typical conditions. The development of expertise, as postulated by the two-stage framework, offers a good example of this. It is indeed possible that the decrease of activity in the first stage may help the unmasking and thus re-use of the mediotemporal lobe, allowing the occurrence of the second stage. We also agree with Anderson when he proposes that unmasking must not be seen as passive. From our point of view, functional neural reorganization occurs through the use of

knowledge structures. The efficiency of these structures is a necessary condition. However, the biological reasons that undergird such processes are unknown.

Experts: Re-using spatial processe*s. 2) "Second, and perhaps less obvious, neural reuse would appear to support and encourage procedural and behavioral reuse."* Guida et al. (2012) provided an explanation of the cognitive processes that both cause and are the consequence of the two identified patterns of brain activity in expertise studies. The first stage – decrease of cerebral activity – has been linked to chunking (Chase & Simon, 1973; Cowan, 2001; Gobet et al., 2001). When practice begins, individuals start binding various domain-specific patterns (e.g., in chess, configurations of pieces) together, which ultimately result in a compression (Mathy & Feldman, 2012) of the elements into one structure, a chunk. Once chunks are built, separate domain-specific patterns can be processed as one element, which means that less cognitive resources are needed, and this is reflected as a reduction of brain activation to perform a domain-specific task. As a consequence of practice and expertise, chunks grow in size (e.g., Cowan, Chen, & Rouder, 2004; Chen & Cowan, 2005) and complexity (e.g., Chase & Simon, 1973; Gobet & Simon, 1996) and with years of training, they become high hierarchical chunks: knowledge structures. These structures (Ericsson & Kintsch, 1995; Gobet & Simon, 1996) allow experts to encode information in episodic long-term memory in a fast and reliable fashion even in conditions typical of working memory tasks (rapid presentation of several elements), which is not possible for novices using similar cell assemblies in the mediotemporal lobe.

As pointed out above, to be able to use episodic long-term memory in a fast and reliable fashion, individuals must develop specific knowledge structures. This illustrates how human beings, "repurpose our behavioral routines in multiple circumstances for myriad cognitive

ends" (Anderson, 2015, p. 16). A well-known example in the domain of expertise is the *method of loci*, which is thought to be the first (internal) mnemonic (Worthen & Hunt, 2011; Yates, 1966), initially proposed by Simonides of Ceos more than two millennia ago. In ancient Greece, orators would visualize a sequence of familiar locations (in their house or a familiar route with salient locations) before a speech, and use them to mentally store important words. Subsequently, during their speech, they would take a mental tour and retrieve each word through the familiar locations. This technique is still in use among expert mnemonists (Pridmore, 2013). Maguire, Valentine, Wilding, and Kapur (2003) revealed the functional cerebral pattern of these mental walks by comparing mnemonists with all-comers. They found comparable activations in both groups in prefrontal working memory areas, but specific activations for the mnemonists, in the left medial superior parietal cortex, in the bilateral retrosplenial cortex and in the right posterior hippocampus (for a similar pattern see also Pesenti et al., 2001); these regions are important for episodic memory and crucial for spatial memory and navigation (e.g., Burgess, Maguire & O'Keefe, 2002). Therefore, it seems that with hours of training, mnemonists are capable of using the mental image of their house (or of a route) as a slotted schema and transfer the incoming information from working memory to long-term memory by associating the new information with each slot (the familiar locations), instead of simply storing the information in working memory. The consequence of the use of the method of loci is an increased memory capacity and cerebral functional reorganization.

This example clearly shows how experts reuse spatial cognitive processes to encode verbal information. These elements are linked to the point 7 of Anderson's précis, "Reuse, interaction, and "higher-order" cognition," and perfectly illustrate the fact that "we have found ways to reuse our physical capacities to augment our mental ones; in a process

supported by neural reuse" (Anderson, 2015, p. 16). Interestingly, a similar process has also been found in "all-comers". Van Dijck and Fias (2011, see also Guida, Leroux, Lavielle-Guida, & Noël, under review) showed that verbal information processed in immediate memory was mentally organized from left to right based on the order of presentation. This suggests that order in working memory could be coded through spatial positional tagging (Abrahamse, van Dijck, Majerus, & Fias, 2014; Guida & Lavielle-Guida, 2014). Based on this idea, Guida and Lavielle-Guida (2014) proposed that spatial positional tags in all-comers were comparable to the spatial locations of expert mnemonists, proposing the generic term of spatialization. The final twist that links all-comers to expertise is that the left to right spatial positional tagging observed in all-comers could be due to expertise in reading and writing.

Experts vs. Novices: same working-memory tasks but different processes and cerebral substratum. *3) the third implication…not every cognitive achievement…need be supported by a specific targeted adaptation.* As emphasized by Anderson, the last implication follows neatly from the previous points. Indeed, we believe that the assemblies of neurons that code for location did not evolve for encoding and retrieving words like in the method of loci. This example enters in a much wider picture when taking into account working memory. It is well-established that prefronto-parietal areas are crucial for working memory in all-comers (Cowan, 2011; Postle, Berger, & D'Esposito, 1999; Postle & D'Esposito, 1999; Todd & Marois, 2004; Vogel & Machizawa, 2004). However, as highlighted above (see also Guida et al., 2012, 2013), when experts execute working memory related-tasks within their domain of expertise, completely different brains areas are activated (e.g., the mediotemporal lobe). In this case, expertise via new assemblies of cells allows experts to circumvent the limits of working memory by using a part of episodic long-term memory. This shows that a same

cognitive achievement (here working memory task) needs not to be supported by a specific targeted adaptation.

Conclusion. The neural reuse framework proposes that the same assemblies of cells can be used for different cognitive functions or tasks in different contexts. Research into the neural implementations of expertise supports Anderson's (2014) hypothesis that brain activity decreases and becomes more focalized when a skill is learned. However, another pattern of results in the expertise literature was not envisaged by Anderson – a change of the set of networks used to perform a working memory task as a function of expertise. We presented an explanation of how this effect can be explained by the concept of neural reuse.

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