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COGNITIVE NEUROSCIENCE OF WORKING MEMORY: A PROLOGUE

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The roots of the concept of working memory and the bases for its exploration within cognitive neuroscience can be traced all the way back to the realization that human behavior cannot be fully explained through specifying the stimulus-response relations, as purported by the prevalent behavioral paradigm at the time. Rather, to be able to explain human behavior and experience one has to take into account the ways that information provided by outside stimuli gets processed, manipulated, combined and related to the previous experiences before it is actually used to guide behavior. Tolman (1948) put that down very clearly: "We assert that the central office itself is far more like a map control room than it is like an old-fashioned telephone exchange. The stimuli, which are allowed in, are not connected by just simple one-to-one switches to the outgoing responses. Rather, the incoming impulses are usually worked over and elaborated in the central control room into a tentative, cognitive-like map of the environment. And it is this tentative map, indicating routes and paths and environmental relationships, which finally determines what responses, if any, the animal will finally release."

To try to figure out and explain, what goes on in the "control room," a whole new set of methods and metaphors was needed. The developments in the areas of communication technologies, information theory and computing led to the establishment of the information-processing (IP) paradigm. The mind and its substrate, the brain, were understood as a system for processing and storing information, similar to a computer, which became the prevailing metaphor. Adopting a decompositional strategy the goal of what became known as the *cognitive paradigm* was to explain the capacities and properties the human mind possesses in terms of characteristics of the parts of its cognitive system. The basic assumption has been that the brain enables a person to have these capacities and properties by virtue of having specific information-processing components operating in a specific way. This approach can be compared with reverse engineering trying to figure out the design of a machine by studying its component parts, their properties, connections and interactions (Atkinson, 1998).

To be able to process it and have it available at a later time, the information has to be stored. The concept of memory therefore became an important one within cognitive paradigm and a number of theories of memory were proposed (e.g. Atkinson and Shriffin, 1968). For the execution of complex cognitive abilities and for the control of an ongoing goal-directed behavior, a general-purpose short-term store seemed to be an especially important one. Any kind of information processing system that manipulates, integrates or analyzes information, needs to have the ability to store the relevant information, the intermediate products and the results of manipulation at hand. Any kind of a system that needs to flexibly choose and execute behavioral plans needs to have the ability to hold that information online. Miller et al. (1960) explicitly wrote: "When we have decided to execute some particular Plan, it is probably put into some special state or place where it can be remembered while it is being executed. We would like to speak of the memory we use for the execution of our Plans as a kind of quick-access, 'working memory.'" (p. 65), and so marked the first use of the term.

The term *working memory* was subsequently used in computational modeling approaches (Newell and Simon, 1972), in animal learning studies that required the participant animals to hold information across a number of sequential trials (Olton, 1979), and in cognitive psychology, where it has been applied to a short-term memory (STM) store (Atkinson and Shiffrin, 1968). But it was Baddeley and Hitch (1974) who first explicitly explored the role of temporary information storage as a common system that is involved in the performance of a wide range of complex cognitive tasks, and with that started the scientific endeavor of working memory research.

A multidisciplinary research framework gets adopted

The study of human mind and brain has never been limited to one scientific discipline. The subject has been tackled by a number of disciplines, each addressing the subject from its specific point of view, using the methods, conceptual tools and research paradigms that were developed and shaped through the history of the discipline and adjusted to the specific questions it tried to answer. Though they were initially difficult to relate to one another, the rise of cognitive paradigm and adoption of information processing approach provided a much-needed common conceptual system that enabled the findings of individual disciplines to be related and combined. Cognitive psychologists were able to build computational models and computer simulations of their theories. Neuropsychologists could use models of normal brain function to explain cognitive dysfunctions after brain damage and to plan appropriate rehabilitation programs. Neuroscientists were able to use models of functional architecture to guide their research efforts in

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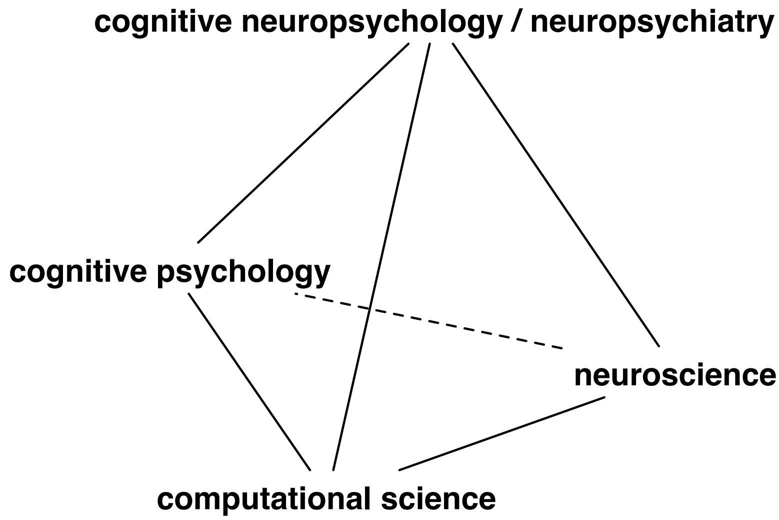

Fig. 1. The fields of research constituting the pyramid approach to research in cognitive neuroscience.

finding relevant neuroanatomical structures and neurophysiological mechanisms, and at the same time provide cognitive psychologists with important ideas and constraints for their theories.

The existence of a bridge, however, does not ensure its actual or most efficient use. Even though combination and confrontation of evidence from different fields of cognitive neuroscience enabled some important breakthroughs, it is not always practiced or even readily accepted. A systematic research framework that would propose a way to coordinate research efforts and encourage consideration of findings from different fields of cognitive neuroscience when developing theories of human brain and mind might therefore be helpful.

Extending Kosslyn's (1996) cognitive neuroscience triangle framework we propose a pyramid approach to research in cognitive neuroscience in which four lines of research have to be considered when developing comprehensive models of mind/brain (Fig. 1). First, the capacities and properties that the model is to explain need to be described in detail and a functional architecture by virtue of which the mind/brain enables the person to have those properties and capacities needs to be put forward. This is the role of cognitive psychology. Second, working computational models of cognitive functions that specify in detail the proposed theoretical assumptions and are based on known neurobiology of the brain need to be built. That is the domain of computational science. Third, the actual anatomical structure and physiology of the brain need to be taken into account to be able to explain how the cognitive functions are actually instantiated in the brain. That is the purview of neuroscience. Fourth, cognitive dysfunctions following specific brain damage caused either by brain injury, neurological or psychiatrical disease, need to be studied to provide further constraints and tests of the theory. That is the realm of cognitive neuropsychology and neuropsychiatry. Each of the stated lines of inquiry contributes unique and necessary information. This is the framework we adopted as the backbone of the issue.

The aims of the issue get explained

There are two aims that generated the idea of this special issue and guided its development. First, the special issue aims to provide an overview of the current research in cognitive neuroscience of working memory, both in the terms of the recent findings, as well as in terms of the research methods being used. To present a comprehensive overview, the cognitive neuroscience pyramid framework (Fig. 1) was followed. Second, since it is the integration of findings in a multidisciplinary framework that will ultimately enable us to unravel the mysteries of the human brain, and the mind that it gives rise to, the present special issue hopes to encourage a purposeful, systematic multidisciplinary approach to research in cognitive neuroscience by illustrating it with the application of such approach to working memory research.

The overview of the issue is presented

The issue is organized in three parts. The first part consists of broad review papers that introduce the main theoretical models and views of working memory and some of the approaches to the study of working memory. The second part provides problem-oriented review papers that introduce individual research questions and possible answers that cognitive neuroscience offers today. The third and final part of the issue gives space to a number of empirical papers that further illustrate the variety of specific research questions being addressed and methods used by cognitive neuroscientists.

The issue starts off with a paper by Repovš and Baddeley that presents the current state of the arguably most influential model of working memory, the multi-component model of working memory proposed initially by Baddeley and Hitch (1974), and reviews recent empirical findings offered by behavioral studies. The issue continues with a paper by Postle, arguing that rather than postulating specialized brain subsystems that act as buffers for storing and manipulating information in working memory, working memory should be understood as a flexible system that recruits individual brain subsystems as needed to perform the working memory tasks.

Six subsequent review papers introduce some of the approaches used to study working memory, and their findings. Jarold and Towse show how the study of individual differences can shed light on the structure of a cognitive system such as working memory. Mueller and Knight provide examples of how human brain lesion studies can provide important data for testing and developing models of working memory. Honey and Fletcher continue with an overview of advantages and pitfalls to consider when extending the brain lesion approach of cognitive neuropsychology to cognitive dysfunctions found in psychiatric population, specifically patients with schizophrenia, and show possible solutions such as the use of psychopharmacological models of disease in healthy human subjects. Barch then follows with a more detailed analysis of how studies of working memory in schizophrenia compare with existing human and non-human primate data and bear on the models of working memory. Looking at another alternative to brain lesion studies, Mottaghy introduces the use of transcranial magnetic stimulation (TMS) as a method of temporary virtual lesioning of the brain. Finally, a paper by Schloesser, presenting structural equation modeling as a method of assessing the brain network employed in performing working memory tasks, concludes the first part of the issue.

The second part of the issue starts by focusing on the computational approaches to the study of working memory. A paper by Hazy et al. demonstrates how important advances in understanding cognitive systems can be achieved by using computational modeling to specify computational and neural mechanisms involved in its operation. While the first paper focuses on how larger brain systems interact in performing complex cognitive tasks, the following papers, by Durstewitz and Seamans, Compte, and Tanaka explore how neurocellular properties and their interaction in neural networks translate to functional characteristic of the nervous system enabling computational mechanisms that give rise to cognition. Taken together these papers provide an exciting view of how computational modeling can build bridges between neurobiology and cognition.

The remaining papers of the second part focus on uncovering individual neural mechanisms and representations that jointly form working memory. Reflecting its popularity in cognitive neuroscience research due to relative ease with which it relates cognitive performance to brain activity, most of the papers in this section are based on functional magnetic resonance imaging (fMRI) applied to research on spatial working memory (Curtis), proactive interference (Jonides and Nee), coding of order (Marshuetz and Smith), executive functions (Collette, Hogge, Salmon and Van del Linden), and delayed task performance (Rypma). The strength of electro- and magnetoencephalography (EEG, MEG) in elucidating brain activity and large-scale neuronal synchronization on a finer time-scale is demonstrated in a paper by Jensen, exploring the use of temporal segmentation as a possible mechanism of maintenance of multiple items in working memory. Funahashi continues with electrophysiology, taking it farther to multiple single cell recordings in monkeys, enabling the exploration of population vectors of activity, functional interaction among neighboring neurones and their dynamic modulation in working memory tasks. Turning the focus to neuropharmacology, Graham and Castner explore the fine balance between the multiple mechanisms of dopamine modulation in working memory. The second part concludes with a paper by Ranangath that integrates findings from multiple approaches in a true multidisciplinary manner to explore how different cortical areas interact to form and maintain visual memories.

The issue closes with a wide variety of empirical papers covering issues from cross-modal working memory (Ohara, Lenz and Zhou) to modulation of working memory by social and affective factors (Park, Gibson and McMichael), employing a variety of methods including MEG, fMRI, neuropharmacology and behavioral studies.

The guest-editors bid farewell

Designing and editing this special issue has been an interesting journey and learning experience. If anything, it made evident that the extent and diversity of research being conducted in working memory make it impossible to present it comprehensively in a single journal issue. We do hope, however, that it provides the *Neuroscience* readers with a broad sketch of the area, offers them a chance to "dip their toes" in the subject, and encourages them to further explore the multidisciplinary research in working memory.

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