error. Three decades of neural modeling of behavioral and brain data about STM and LTM (e.g., Bradski et al. 1994; Brown et al. 1999; Carpenter & Grossberg 1991; Fiala et al. 1996; Grossberg 1968; 1980; 1982; 1987; 1988; 1999; Grossberg & Myers 2000; Grossberg & Williamson 2001; Page 2000) suggest that STM and LTM are intimately linked, but embody different organizational principles, are realized by different mechanisms, and obey different laws. Available models clarify cellular neural mechanisms of STM/LTM and their integration into brain systems – including how STM per se differs from prefrontal working memory – that can temporarily store multiple events and their order in STM.

STM involves activation of cells that receive signals from axons whose synapses contain adaptive weights which encode LTM. Suitable (but not all) cell activations in STM can lead to learning and LTM within abutting synapses whose axons are active at that time (associative learning). Later activation of these axons can read out LTM into cellular STM activations. Although this description clarifies why STM and LTM are closely linked, it does not completely support the authors' claim that "long-term memory and short-term memory are different states of the same representations." To see this, imagine that two different sets of cells read-out their LTM into the same target cells at different times. Then the STM patterns that develop will be different. STM combines LTM read-out from multiple cells into a composite STM pattern. Moreover, "short-term memory maintenance of the items" does not necessarily consist "of reactivation of the long-term memory representations." STM can be maintained by recurrent interactions that are different from those which read-out LTM. Indeed, a key role for working memory is to temporarily store an unfamiliar sequence of events before learning can chunk it into a new LTM representation.

Working memories cannot work well unless they operate at correctly defined processing levels and obey correctly constrained laws. Many experiments support the proposal that a working memory represents sequences of "items" that have individually been unitized through prior learning experiences. Familiar feature clusters that are presented within a brief time interval become items by being categorized, or unitized, in LTM at a processing stage that occurs before the working-memory stage. As item categories are processed through time, they input to a working memory in which multiple items are simultaneously stored as part of an evolving spatial pattern of activation across a network of item representations. This spatial pattern represents both item information (which items are stored) and temporal order information (the order in which they are stored). Individual items can be recalled when a rehearsal wave nonspecifically activates the entire working memory. The rehearsal wave allows the most active items to be recalled first, after which they inhibit their own representations using recurrent inhibitory feedback, so that less active items can also be recalled in the order of their relative activity (Grossberg 1978a; 1978b; 1982; Koch & Ullman 1985; Page & Norris 1998).

A number of articles have modeled such "item-and-order working memories" to explain data about free recall (Bradski et al. 1994; Grossberg 1978a; 1978b; Page & Norris 1998), reaction time during sequential motor performance (Boardman & Bullock 1991; Grossberg & Kuperstein 1986/1989), errors in serial item and order recall that are a result of rapid attention shifts (Grossberg & Stone 1986a), errors and reaction times during lexical priming and episodic memory experiments (Grossberg & Stone 1986b; McLennan et al. 2003), data concerning word superiority, phonemic restoration, and backward effects on speech perception and word recognition (Cohen & Grossberg 1986; Grossberg & Myers 2000), and so forth. All of these working memory models satisfy two simple postulates (Bradski et al. 1994; Grossberg 1978a; 1978b).

The key postulate, called the "LTM Invariance Principle" proposes how working memories, which encode a type of STM, enable unitized representations of lists of items to be stably learned and stored in LTM. Thus STM and LTM are linked, but in a way not described by the authors, and one that does not conflate their different roles. For example, after learning the words MY and SELF, suppose that the word MYSELF is temporarily stored in working memory for the first time. How does a listener learn a new word representation for MYSELF without erasing the previously learned word representations for MY and SELF from LTM? When such learning occurs in an unsupervised fashion in real time, as it does when a child learns a language, a poorly designed working memory could easily cause catastrophic forgetting of MY and SELF when learning MYSELF.

The second postulate requires that the maximal total activity of the working memory is finite and, indeed, independent of the total number of active cells. This postulate implies the limited capacity ("the number of pointers"; see target article, Abstract) of working memory. Because total working-memory activity cannot increase indefinitely with the number of activated cells, some cells must be inhibited to enable other cell activities to be stored.

Such working memories are called STORE (Sustained Temporal Order REcurrent) models. Remarkably, specialized recurrent on-center off-surround networks satisfy both STORE postulates. Recurrent on-center off-surround networks are ubiquitous in the brain because they enable distributed input patterns to be processed without a loss of sensitivity by their target cells (Grossberg 1980). Thus, designing a working memory reduces to specializing an ancient neural design. This design is not, however, the same as the design of LTM at the synapses that connect cells at which STM occurs. Properties of synchrony, attention, and consciousness naturally emerge in neural systems that respect these differences between STM and LTM (Grossberg 1999).

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More memory?

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Abstract: Modern investigators of cognition ask about the conditions under which faculties occur rather than about their existence. This tendency, combined with the axiom of parsimony, emphasizes a paradigm shift in the fundamental principles of economic thought in science, mimicking evolutionary conceptualizations. The Ruchkin model of memory-related brain activity replaces less economic models. From interdisciplinary approaches, proceduralist models for other memory-related processes analogously support this model.

A paradigm shift in scientific investigation has occurred over the last third of the twentieth century. Investigators of cognitive processes are increasingly likely to research the conditions under which faculties can be observed, rather than ask whether and where a cognitive faculty exists (cf. Brown & Campione 1973; Cole & Medin 1973; Grote 2003; and Grote, submitted, on mediation and self-instruction as memory). Principles and procedures shift accordingly. Combined with a much older principle in science, this shift is of relevance to Ruchkin and colleagues' target article. Pearson reminded us, in 1892, that William of Occam's Razor, or the axiom of parsimony, forbids postulating needless multiple existences for describing events (Pearson 1943). It is one of the most fundamental principles of economic thought in science.

Ruchkin and colleagues' proceduralist or activation model economically replaces patterns of activities used by same memory systems for models that postulate the existence of more systems. Ruchkin and colleagues propose that different patterns of brain activity in short-term and long-term memory can describe memory processes without needing storage of memory in additional

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subsystems or buffers of short- and long-term memory systems. This description of brain activity results from observing patterns of brain activity under various conditions. In their view, a variety of patterns, activated by fewer systems, accounts for short-term memory as well as for long-term memory processes.

This economy in scientific description may mimic the economy that evolution may have selected for natural events. Allowing many permutations by a few entities, perhaps based on algorithms yet to be described for brain activity, is most elegantly seen in DNA coding. The principle of parsimony functions at the language level of science, as it does at the level of observable events in nature, selected by evolutionary processes. Phylogeny provides for the susceptibility of various patterns to occur in ontogeny under various conditions. In other words, an algorithm pervading functions selected by evolution, may go like this: Multiple patterns in few structures, to account for occurrence under multiple conditions, are more economical than multiple structures to account for a variety of patterns. However, to verify this will take more research on the conditions under which many memory functions occur, including more research on more memory proceduralist accounts of the kind provided by Ruchkin and colleagues.

Within their discipline, Ruchkin et al.'s replications across data figures, across many conditions, and across research results by other investigators, seem to lend convincing support to an economic model of brain activity in memory processes. On an interdisciplinary level, proceduralist or activation models in other memory-related processes analogously support Ruchkin et al.'s model. Grote (submitted) discusses an experimental model of self-instruction as a form of memory mediation, in which procedures can control and account for problem-solving facilitated by prompted self-instruction, sometimes needing procedures for prompting commitment to spend attention to and to remember self-instruction. That model requires no special status for a "self," and it requires no separate cognitive-behavioral or neuropsychological structure or meta-structure to be invoked for more memory, in order to have more economic functioning, in problem-solving. The present commentary welcomes Ruchkin and colleagues' findings as a contribution to clarifying a number of concepts related to memory, including self-control, self-regulation, and especially self-instruction, and for purging the need for extra systems from cognitive-behavioral conceptualizations.

A few additional bits of information, however, would have been useful in Ruchkin et al.'s report – especially some relevant for cognitive-behavioral developmental models. Such models regard the modality-specificity of verbal and visuo-spatial dimensions under different conditions of development to be of importance (e.g., Jones 1973 on the visual, Zeaman & House 1979 on two- and three-dimensional stimuli). Hence, I would have liked to see some information on the age and educational level of participants. I also wondered whether they were different or same cohorts of participants that were represented in the various data figures.

A few more (benign) points of criticism: I missed seeing a figure on semantic *relatedness* (sect. 3.7) for comparison with Figure 10 for semantic *unrelatedness* (sect. 3. 7). More information about the unpublished research (cited at the end of sect. 3.2 and in sect. 3.4) – and with which colleagues – could have been given in a note; along with further clarification of the Ruchkin (1997a; 1997b) studies, including mention of the colleagues involved here.

Finally, it would be instructive if "Phreneurology" measurement, such as described in the Appendix, could be schematized in a figure, as it is relevant to and referenced in nearly each figure of the target article. (I deliberately call the measurement "phreneurology," tongue in cheek, because it is peculiarly reminiscent of old phrenological concepts for mapping scalp topographies.)

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Another artificial division – and the data don't support it

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Abstract: Evidence for the contribution of the neocortex to memory is overwhelming. However, the theory proposed by Ruchkin et al. does not only ignore subcortical contributions, but also introduces an unnecessary and empirically unsupported division between the posterior cortex, assumed to represent information, and the prefrontal cortex, assumed to control activation. We argue instead that the representational power of the neocortex is not restricted to its posterior part.

Arbitrary divisions are quite popular in science, and, because they help to structure the respective fields, they might make sense for a certain period of time, even if they ultimately turn out to be wrong. So, for example, quite a substantial amount of research was driven by the idea that short-term and long-term memory are realized by distinct storage systems (Atkinson & Shiffrin 1968). In accordance with a number of previous theories based in the fields of Experimental Psychology (e.g., Anderson & Bower 1973), in Cognitive Neuroscience (Fuster 1997), and in Neural Network Modeling (e.g., McClelland et al. 1995), respectively, Ruchkin et al. want to repudiate the existence of this division. Instead, short-term memory is understood as the activated part of long-term memory.

So far so good, but we nonetheless see a problem in the target article. We do not want to discuss whether one more theory stating the nondistinction between short-term and long-term memory was needed. In the same way, we do not want to dispute the experimental quality of the studies presented – even though in almost all cases the comparisons are confounded by differences in the overall difficulty of the conditions examined. (Therefore, the data do not allow for unequivocal interpretations.) Instead, we want to focus on the theoretical contributions of Ruchkin et al.

The main problem we see is that the authors introduce a new artificial division, namely, between the posterior cortex (the region where the memory representations are assumed to be located) and the prefrontal cortex (where an "attentional pointer system" is assumed to control and maintain the activation in the posterior cortex). For the sake of clarity, we break this idea down into three parts in order to illustrate its implications. In addition, we comment on the basic assumptions behind the artificial division.

According to Ruchkin et al., the cortical memory capabilities are assumed to be restricted to the posterior cortex. There is, however, quite substantial empirical work supporting the idea that the anatomical basis for memory is *not* restricted to the posterior cortex. To give just a few examples, it is assumed that motor representations are stored in the motor cortex and probably in the supplementary motor area (see, e.g., Nyberg et al. 2001), which are both *not* part of the posterior cortex, and that these representations are reactivated when the motor information is retrieved (Heil et al. 1999). Similarly, the premotor cortex is also activated when manipulable objects, as opposed to non-manipulable ones, are maintained in working memory (Mecklinger et al. 2002). Recent evidence also shows that over anterior scalp areas different event-related potential (ERP) topographies are evoked, if either verbs or nouns are accessed (Khader et al. 2003). Finally, the role of the left frontal cortex (certainly not a part of the posterior cortex) in the representation of verbal and/or semantic information in both short-term and long-term memory tasks cannot be underestimated (see, e.g., Heil et al. 1996; Paulesu et al. 1993). To sum all this up, the idea that memory representations are restricted to the posterior cortex does not survive empirical tests – leaving aside the fact that Ruchkin et al. don't even specify what the "posterior" cortex does actually embrace.

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