



Figure 1 (Speed et al.) Holographic data storage and retrieval. Inset illustrates an interference pattern on film that is the physical storage of the holographic image.

Novick 1988). This might also cause enhancement of a particular memory (e.g., the von Restorff effect; Hunt 1995).

Additional implications of the holographic analogy include:

1. The fact that a single beam of a particular frequency recalls the entire image may be analogous to reintegration (Roodenrys & Miller 2008).

2. The capacity for storage and reuse increases with the number of variables used in defining neural and circuit behavior (Kalman et al. 2004; Plate 1995; Psaltis & Burr 1998; Sutherland 1992).

3. The number of parameters defining neural and circuit behavior in a given organism should predict behavioral/cognitive complexity, and such complexity should scale similarly to the predicted capacity.

As indicated above, tests of predicted capacity and interference can be done using computational simulations, experiments with networks in preparation, or engineered networks of neurons.

In the past, the optical holography analogy has been criticized (e.g., Wilshaw et al. 1969). Certainly, the analogy does break down in certain places – for example, the fact that any piece of the photographic plate encodes the entire image, thus destroying some parts of the plate, merely degrades image quality rather than creating an analogue to aphasias seen in humans. However, using the holographic analogy as a starting point for hypothesis development might provide a foundation from which the physical mechanisms of neural reuse might be identified.

NOTES

1. The authors of this commentary are employed by a government agency, and as such this commentary is considered a work of the U.S. government and not subject to copyright within the United States. Each commentator contributed equally to this response and are thus listed in alphabetical order.

2. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy’s National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Massive redeployment or distributed modularity?

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Abstract: In distinguishing itself from other distributed approaches to cognition, Anderson’s theory of neural reuse is susceptible to some of the same criticisms that have been leveled at modular approaches. Specifically, neural reuse theories state that: (1) the “working” of a given brain circuit is fixed, rather than shaped by its input, and (2) that high-level cognitive behaviors can be cleanly mapped onto a specific set of brain circuits in a non-contextualized manner.

The target article does an excellent job of exploring the behavioral, neural, and theoretical evidence supporting the idea that brain regions are reused in the service of many different cognitive functions and that traditional, modular approaches to neural architecture may be misguided. This viewpoint echoes other recent critics of contemporary cognitive neuroscience (e.g., Uttal 2001) and fits well alongside related distributed, emergent approaches to cognitive functioning (Rumelhart & McClelland 1986; Thelen & Smith 1994; Varela et al. 1991). A distinguishing feature of Anderson's neural reuse framework is that it highlights how local neural circuits with *fixed* "workings" may be combined in evolutionary (or developmental) time to support new cognitive "uses." However, we are concerned that some of the same criticisms that have been leveled at modular approaches to the mind may also pose problems for the current formulation of the neural reuse theory.

First, much like classical modular views of mind, Anderson's theory of neural reuse de-emphasizes the role that the immediate environment plays in the development of the functional properties of a particular neural circuit (Fodor 1983; Pinker 1997). In fact, the target article explicitly claims that the working of any given anatomical brain site is fixed, in stark contrast to classical PDP (parallel distributed processing) models. However, there is evidence that the function of a given neural circuit may be largely shaped by the structure of its input. For example, Sur and colleagues (Sharma et al. 2000; von Melchner et al. 2000) surgically rewired the optic tract of a ferret so that primary auditory cortex received visual input from the eyes of the animal. Not only did the ferret seem to develop normal visual (and auditory) behavior, but also the circuitry in auditory cortex exhibited many of the properties traditionally associated with visual cortex, such as orientation selective cortical columns. This suggests that the working of circuits even in the most evolutionarily ancient cortical regions is not restricted to any particular modality, let alone any specific function. Such flexibility provides evidence in favor of computational mechanisms that derive their function based in part on the statistical structure of the input (Rumelhart & McClelland 1986).

Second, while Anderson's theory of neural reuse rejects the idea that high-level cognitive functions (e.g., "language comprehension") can ultimately be mapped onto any single brain module, the approach still calls for the one-to-one mapping between these high-level functions and a specific, distributed set of neural circuits. However, it may be the case that distinct instances of what we would label as the *same* cognitive behavior might actually emerge from the distributed activation of *different*, contextually variable sets of neural circuits. For example, although visual object recognition has been shown to automatically activate motor brain regions (Chao & Martin 2000; Tucker & Ellis 1998), very different motor circuitry might be recruited to *recognize* a chair when you are tired and want to sit down than when you need to reach something on a high shelf. There may also be individual differences across a population in what neural resources are recruited for a particular cognitive task. For example, some people seem to readily recruit direction-selective neurons when listening to stories describing both literal and metaphorical motion, whereas others do not, even though both groups *comprehend* the story (Toskos Dils & Boroditsky, forthcoming). Thus very different neural representations might subservise the very same high-level cognitive behavior (i.e., "object perception" and "language comprehension") both within and across individuals. This suggests that it may be a *category mistake* to try to reduce complex, person-level cognitive phenomena to a unique set of neural circuits (Ryle 1949). Rather, these mental operations are always a contextually bound, emergent function of the history of the organism, the immediate environment, and the bodily state of the organism (Thelen & Smith 1994).

In sum, while Anderson's theories of neural reuse offer a much-needed counterpoint to traditional, modular views of neural architecture, they still suffer from some of the same

difficulties these modular views have in accounting for complex cognitive behaviors that develop over the course of learning and experience. Dynamic models of cognitive function preserve many features of the neural reuse framework that account for data unexplained by massive modularity models. They should be preferred because, unlike neural reuse models, they also predict that the function of a given circuit should change as the structure of its input changes, and they do not require that high-level cognitive functions cleanly map onto specific cortical circuits. These approaches currently provide the additional benefit of computational models that can be used to make precise predictions about the development of cognition function. Proponents of neural reuse should point to specific ways in which they can accommodate the limitations of the current formulation of neural reuse theory.

Belling the cat: Why reuse theory is not enough

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Abstract: I agree with Anderson's approach to reuse theories. My main concern is twofold. Anderson assumes certain nomological regularities in reuse phenomena that are simply conjectures supported by thin evidence. On the other hand, a biological theory of reuse is insufficient, in and of itself, to address the evaluation of particular models of cognition, such as concept empiricism or conceptual metaphor.

I would first like to welcome Anderson's target article. Extant cognitive neuroscience and neuroimaging studies, as well as the growing importance of biological analyses in cognitive science, increasingly show the unsuitability of a modular approach to cognition. In this situation, a new framework is required to model the functional architecture of cognitive processes in the nervous system. Anderson's article is a remarkable effort in this direction. I agree with his general approach to the issue. My main concern, though, is twofold. On the one hand, Anderson assumes certain nomological regularities in reuse phenomena that are simply conjectures supported by shaky evidence. On the other hand, a biological theory of reuse by itself is inadequate for the task of evaluating particular models of cognition, such as concept empiricism or conceptual metaphor. We need an independent characterization of cognitive phenomena, a model that we currently lack.

First, extracting biological regularities from evolutionary phenomena is not a straightforward issue. Elsewhere (Vilarroya 2001), I have suggested that cognitive systems are constrained by what I called "bounded functionality," which accounts for the dynamics of the functional paths leading to solutions to adaptive problems. One of the bounded functionality constraints is what I call the "bricoleur constraint," defined as the fact that natural selection favors the shortest design path. In other words, the solutions to adaptive problems have to take into account the resources that were available to the system before the adaptive problem appeared. The bricoleur constraint is the evolutionary characterization of the reuse approach. However, the bricoleur constraint can be realized in many ways for any evolutionary phenomenon. For instance, Anderson's principle, that "older areas, having been available for reuse for longer, are *ceteris paribus* more likely to have been integrated into later-developing functions" (sect. 1.1, para. 1), can be a good starting point, but it cannot be taken as an evolutionary law. Evolutionary biology is full of surprises; older areas can serve a small