Title
Brain neural activity patterns yielding numbers are operators, not representations

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Further support for this conclusion comes from the following auditory duration judgment task (Wearden et al. 2007). Participants were presented with a standard stimulus and a comparison stimulus consisting of filled or unfilled auditory durations, and they had to judge if the two stimuli had the same duration or different durations. There were four conditions, filled following unfilled (UF) durations, unfilled following filled (FU), filled following filled (FF), and unfilled following unfilled (UU) durations. The temporal generalisation gradients (i.e., functions plotting the proportion of "same duration" answers over duration differences between standard and comparison stimuli) showed slightly but significantly different shapes for FF trials compared to UU trials and markedly different shapes between FU and UF trials (see Fig. 1). These findings suggest that different notations of auditory stimuli can take distinct processing forms in the brain, providing additional support for the claim that durations are represented concretely.

In conclusion, the reported evidence suggests that not only number, but also time can be represented concretely in the brain. This shared characteristic is in line with the idea of a general magnitude system, which codes time, space, and quantity (Walsh 2003). Both CK&W's and our evidence strongly suggest that a general magnitude system could code different forms of magnitude using concrete representations.

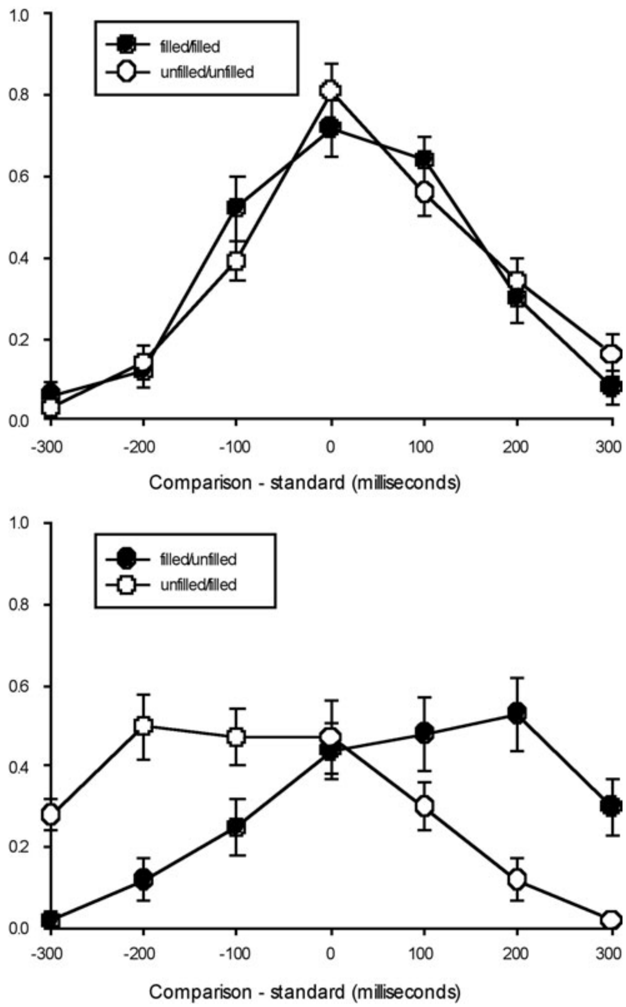

Figure 1 (Falter et al.). Temporal generalisation gradients (mean proportion of "same duration" responses plotted against duration differences between standard and probe stimuli) for comparing filled and unfilled auditory durations. Upper panel: Comparison of filled durations (black circles) versus comparison of unfilled durations (white circles). Lower panel: Filled standards followed by unfilled probes (black circles) versus unfilled standards followed by filled probes (white circles). (Figure from Wearden et al. 2007.)

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Brain neural activity patterns yielding numbers are operators, not representations

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Abstract: We contrapose computational models using representations of numbers in parietal cortical activity patterns (abstract or not) with dynamic models, whereby prefrontal cortex (PFC) orchestrates neural operators. The neural operators under PFC control are activity patterns that mobilize synaptic matrices formed by learning into textured oscillations we observe through the electroencephalogram from the scalp (EEG) and the electrocorticogram from the cortical surface (ECoG). We postulate that specialized operators produce symbolic representations existing only outside of brains.

Cohen Kadosh & Walsh (CK&W) define representations as: "patterns of activation within the brain that correspond to aspects of the external environment" (sect. 2, para. 2). They "differentiate representation from processing" that includes "pre-representation (e.g., visual identification of the digit) and post-representation components (e.g., working memory, response selection)" (sect. 2, para. 2). Thereby, CK&W "argue that the PFC [prefrontal cortex] is not involved in numerical representation, at least not in humans. The PFC is important for some numerical *operations*, but not representations" (sect. 9, emphasis theirs). Figure 5 reflects their view that numerical representations depend on environmental cues that are "coded" initially in "linguistic and imagistic representations." The neural populations in the parietal area provide early "automatic numerical representation," which later transitions to "intentional representation subserved by the PFC neural circuitry."

The authors' distinction between abstract versus non-abstract depends on their restriction of "early representation" to the firings of populations of parietal neurons that are induced or evoked by sensory inputs, and that are revealed by single neuron recordings and areas of functional magnetic imaging (fMRI) activation, while excluding "operations" performed on those populations by the PFC or other parts of the brain.

We share CK&W's views that the direct route to understanding how brains do numbers is by study of activity patterns of the neural populations in question. On experimental grounds, we do not accept their hypothesis that the patterns can be detected by microscopic units, because the numbers of neurons observed by present methods are too few, or by macroscopic fMRI images, because the time scales are too slow. We believe that the patterns will be found, if ever, in mesoscopic brain waves (EEG, EcoG, and the magnetoencephalogram from magnetic sensors fixed around the head [MEG]), which provide the requisite temporal and spatial resolutions (Freeman et al. 2009).

On theoretical grounds, we do not agree that the patterns are representations, because the mesoscopic wave patterns, which we have observed to accompany sensation and perception of invariant conditioned stimuli, lack invariance; the patterns change with variations in context and experience. We hypothesize that our observed patterns are mesoscopic *operators* in the form of synchronized neural oscillations in the beta and gamma ranges, which map the connection patterns in cortical synaptic networks shaped by learning into spatiotemporal patterns of amplitude modulations. We see the concept of representations as a carry-over from Cartesian dualism, which presupposes the primacy of stimuli as determinants of percepts. No, the primary determinants are memories.

Certainly the firings of neurons, when they are appropriately averaged with respect to time and place of repetitive stimulus onset, manifest the presentations of receptor input into cortex, which differ across trials. Sensory-driven and motor-related microscopic activity reported by the authors in the parietal lobes is consistent with the consequences of lesions in the right parietal lobe, first described by Gerstmann (1958): the syndrome of inability to distinguish left from right (disorientation); difficulty in writing (dysgraphia); difficulty with arithmetic (dyscalculia); and inability to name the digits (finger agnosia). The syndrome suggests that skills in elementary arithmetic are closely tied to intentional actions involving use of the hands in symbolic communication that preceded the emergence in evolution of numerical skills (Freeman 2009). These data support the authors' opposition to abstract representation, but the units are too close to the tactical sensorimotor operations of counting and too far from the conceptual strategic operations of arithmetic.

In our view, perception begins with intention and not with sensation. The capacities to foresee a goal, to plan action to achieve it, and to predict the sensory consequences of the action in mammals clearly involve the PFC in the prior structuring of the wave operators in recall of experience. We believe that all species construct neural operators that direct the body in the action-perception cycle (Merleau-Ponty 1942/1963). What distinguishes humans is the capacity to construct hypothetical meta-operators that combine and reshape the ordinary wave packets that we share with other mammals and make symbols. These representations are in, on (e.g., tattoos), or outside the body, serving social planning and communication.

It is easy to suppose that brains work the way computers do, but the metaphor fails. The mathematician John von Neumann wrote:

> Thus the outward forms of *our* mathematics are not absolutely relevant from the point of view of evaluating what the mathematical or logical language *truly* used by the central nervous system is. . . . It is characterized by less logical and arithmetical depth than what we are normally used to. . . . Whatever the system is, it cannot fail to differ considerably from what we consciously and *explicitly* consider as mathematics. (von Neumann 1958, pp. 81–82)

It is likely that the hypothetical symbol-making operators provide the substrate for both words and numbers. How they differ from the ordinary operators is not known. We think that they are not local operators of the kind postulated by CK&W; instead, they are carried by the patterns of activity that cover wide regions in intermittent spatially coherent oscillations (Kozma & Freeman 2008), which are seen in EEG (Freeman et al. 2003; Pockett et al. 2009; Ruiz et al. in press), ECoG (Freeman et al. 2003), and MEG (Bassett et al. 2008). The human brain capacity for this meta-organization can be ascribed to evolution of the most recent enlargements that sculpt the temporal and frontal fossae in hominid endocasts. The added cortices should not be conceived of as loci for storage of numerical representations, but as facilitators of global organization of meta-operators.

The eminent neuropsychiatrist and neuropathologist Paul Yakovlev (1962) described human brains as unique in having areas of cerebral cortex without direct connections to and from the basal ganglia. He speculated that these areas might provide the neural insulation from environmental vicissitudes that is necessary for abstract thought. These areas have not to our knowledge been otherwise identified. We postulate that a marker for them might be the lack of identifying cytoarchitecture that characterizes some neocortical areas having so many seemingly identical neurons that their nuclei appear as grains of dust; hence the venerable anatomical term *koniocortex* (Freeman 2009).

Automatic numerical processing is based on an abstract representation

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Abstract: The goal of the present commentary is to show that past results on automatic numerical processing in different notations are consistent with the idea of an abstract numerical representation. This is done by reviewing the relevant studies and giving alternative explanations to the ones proposed in the target article.

As indicated by Cohen Kadosh & Walsh (CK&W), looking at automatic processing provides an informative insight into the nature of the underlying numerical representations that are relatively uncontaminated by task-dependent strategies. Automatic numerical processing was explored in past research using two main paradigms. The first was the size congruency paradigm, showing that automatic numerical processing takes place when participants intentionally compare the physical sizes of numerical stimuli. Of particular relevance are recent works by Cohen Kadosh et al. (2008e) and Ganor-Stern and Tzelgov (2008), which examined automatic processing of numerical magnitude for digits and number words, and for numbers in Arabic and Indian notations. The second paradigm was the SNARC effect, showing automatic magnitude processing and mapping of magnitude to space when participants perform a variety of tasks that do not require magnitude processing. Relevant for the present context are works that looked at the SNARC effect for digits and number words (e.g., Fias et al. 1996; Nuerk et al. 2005).

The target article authors' conclusion from past studies is that the representation underlying automatic processing is notation-specific. This conclusion is mainly based on the fact that the evidence for automatic numerical processing was not identical for the different notations. In this commentary, I suggest that a notation-specific representation does not necessarily follow from the empirical findings, and I propose alternative explanations for the patterns of findings reviewed in detail in the target article.

First, CK&W have cited a series of studies showing more robust evidence for automatic processing of digits than of number words, and have interpreted this pattern of results as supporting the idea of notation-specific representation. It should be noted, however, that automatic processing is heavily influenced by skill level. People are not equally skilled with extracting numerical information from different notations, but rather, they are more skilled in extracting such information from digits than from number words. As a consequence, automatic numerical processing of number words might be more limited than that of digits. Hence, it might take longer time to occur (Cohen Kadosh et al. 2008e), it might not take place when a verbal task is performed (Fias et al. 2001a), or under