Positing numerosities may be metaphysically extravagant; positing representation of numerosities is not.

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Commentary to appear alongside Sam Clarke & Jacob Beck's 'The Number Sense Represents (Rational) Numbers'

Abstract: Clarke & Beck assume that ANS representations should be assigned referents from our scientific ontology. However, many representations, both in perception and cognition, do not straightforwardly refer to such entities. If we reject Clarke and Beck's assumption, many possible contents for ANS representations besides number are compatible with the evidence Clarke & Beck cite.

Clarke and Beck's argument critically relies on the principle that "our search for the referent of a representation should be biased towards entities we have independent reason to posit in our scientifically informed ontology" (§6). This principle is suspect. Many representations cannot be mapped straightforwardly onto entities in our considered, scientific ontology. For good reason: part of the project of psychology is to understand minds which are unscientific, and whose ontology is mistaken.

Many representations, ranging from past scientists' beliefs in phlogiston to contemporary Americans' beliefs in paranormal phenomena (Moore 2005), are not of entities from current scientific ontology. Representations which do have tighter relationships to scientific entities, meanwhile, are frequently confused. Carey (2009) surveys evidence for "undifferentiated representations" both in children and in the history of science: the confusion of heat and temperature (371-376), and of mass, weight, and density (379-405). Such mismatches between ordinary representational systems and those of current science are not limited to concepts: it is hotly disputed whether *perceptual* colour, odour, or timbre representations have single, consistent referents from our scientific ontology. If they do, these referents may be relational properties partly defined in terms of the perceiver, or convoluted sets of entities from physics like wavelengths and chemical compositions, rather than natural kinds. Even perceptual *spatial* representations do not simply map onto Euclidean space, and must be construed as either frequently inaccurate, or as not representing objective, Euclidean spatial properties (Fernandez &

Farell 2009, Hill 2016, McLaughlin 2016, Prettyman 2019). Clarke and Beck repeatedly accuse numerosity advocates of a double standard, arguing that while number representations are treated as only representing 'numerosity', we do not extend this -osity treatment to other entities. But this double standard is a mirage: representations of weight-mass-density, wavelength-osity (commonly known as "colour") and chemical-composition-osity (odour) have a similarly ambiguous relationship to entities in our scientific ontology.

There are numerous theoretical options for assigning reference to confused or unscientific representations. These include: allowing entities outside our scientific ontology to serve as referents, whether fictional objects, gerrymandered entities like the property grue, or extra-scientific objects; assigning different scientifically sanctioned entities to the same representation in different contexts; assigning indeterminate referents; or assigning no referents at all. We do not need to choose between these options to see that, given the ubiquity of confused representations, Clarke and Beck's bias is not a bias we should adopt. This matters: relying too readily on the claim that the ANS simply 'represents numbers' may lead to overconfidence in predicting its behaviour in scenarios where its connection to genuine number is weaker.

Clarke and Beck's main stated reason for their bias is that it "allows psychological explanations invoking representational content to be integrated with explanations from other sciences, like biology" (§6). However, inter-disciplinary integration is frequently messy, and as a result, similar principles would mislead in similar cases. Consider introducing a bias towards thinking that biological bodies are perfect spheres to allow biology to integrate smoothly with geometry: it is a bias that, if it has any role at all, needs to be extremely weak.

The evidence Clarke and Beck cite is predicted equally well by views on which the ANS traffics in confused representations, and by the view that it always, unambiguously represents number. To take one example, Clarke and Beck admit that the ANS is sensitive to many confounds, such as density and size. They point to success on (amongst others) cross-modal number-based tasks, to suggest the ANS represents number rather than density, size etc. But while such behaviour rules out the ANS unambiguously representing one of the potential confounds in all situations, it is consistent with many possible systems which *confuse* number with other confounds. Such a system might be driven by variation in number *in this situation*, especially if other variables it is sensitive to are not available, whilst ignoring or under-weighting number-specific information in other situations where it produces the very same 'number-representations'.

How can we empirically distinguish between such possibilities? A full discussion of all potentially relevant forms of evidence is beyond the scope of this commentary. But three potential lines of inquiry stand out. Firstly, investigating details of the ANS' computations: Deciding between some of the possibilities Beck and Clarke discuss in their account of congruency effects (§3), such as representations of non-numerical variables affecting the inputs, internal processing, or downstream processing of the ANS, would help. Their emphasis on sensitivity to higher order properties also seems promising, but further investigation is called for: *how* does an implicit commitment to the represented variable being higher order play out in the actual computations, and how consistent is this — are there also situations where the ANS is sensitive to first order properties instead, or even confuses higher and lower order properties? Does the ANS consistently respect any *other* distinctive properties of number? Secondly, what

is the *degree* to which we find sensitivity to number as opposed to other variables across different conditions?   Here, we need to bear in mind that a version of the 'file drawer effect' is likely to be particularly pernicious in this case: results showing *clear* sensitivity to one variable rather than others are more likely to be published. Thirdly, under what conditions do we see failures when the ANS is used in number-based inferences, and can we put any of these failures down to fundamental confusion about number, in a way parallel to results suggesting children confuse weight and density (Carey 2009: 389ff.), or are such confusions extremely hard to come by?

The range of live possibilities for what the ANS represents is vast. Beck and Clarke's reasons for not taking most of that range seriously rely on a principle which, if applied consistently, would block our understanding of many kinds of perception, conceptual development in children, unscientific adult thought, and even the history of science. We should reject this principle, and with it, anything more than weak confidence in the ANS indeed representing numbers.

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