results in a ten-degree-left rotation of the body position, rather than try to model the details of the muscle movements and resulting forces that cause the turn. However, taking this approach to its logical conclusion, the "highest level" of motor commands might be described in terms of desired goals and the "highest level" of perception might be confirmation that the goals have or have not been achieved – in which case the "emulation" required for prediction becomes trivial: It consists simply of making a copy of the goals.

Thus, in both cases – allowing approximate, or high-level, emulation – we are led to consider a continuum, from complete and detailed internal models of the plant, environment, and the measurement process, to extremely simple processes that might suffice for prediction. Much of the evidence cited to support the emulation theory does not distinguish where on this continuum the actual mechanisms might lie (Karniel 2002). Our intuitions tend to be very different when discussing human brains and insect brains, yet the problems are often common ones. The force of the theory – as a predictor of future behavioural or neurophysiological findings – lies in the assumption that the mechanisms, at least for human brains, lie towards the complex end of the continuum. The interesting question is whether there is strong evidence to support this assumption.

Two distinctions concerning emulators

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Abstract: The target article distinguishes between modal and amodal emulators (the former predict future sensory states from current sensory states and motor actions, the latter operate on more abstract descriptions of the environment), and motor and environment emulators (the former predict the results of one's own actions, the latter predict all changes in the environment). I question the applicability of modal emulators, and the generalization to environment emulators.

Grush postulates two types of emulators, modal and amodal. Modal emulators operate at the sensory surface, predicting future sensory states (in some given modality) from current sensory states and motor commands; amodal emulators, on the other hand, operate on deeper descriptions of environmental parameters, predicting future parameters from current parameters and motor commands. Each of these two types of emulator runs into at least one major difficulty.

The difficulty of the modal emulator (of which Mel's models are examples) might be called *sensory aliasing:* Most of the time, current sensory states and motor commands can lead to many (usually infinitely many) future sensory states. Although Grush acknowledges this problem, it is probably worse than he lets on. Let us start by examining two special cases in vision where sensory aliasing *might not* be a problem.

When manually rotating a solid object, if the axis of rotation exactly corresponds to the line of sight, knowledge of the current two-dimensional image and of the motor command to the hand (assuming that this predicts the hand's angle of rotation) is enough to predict future sensory states – they are just rotations of the two-dimensional image by the given angle. This is the kind of rotation studied by Wexler et al. (1998).

In the human eye, optic and geometric centers nearly coincide. As a consequence, when the eye rotates in the head (during a saccade, for example), the two-dimensional optic array simply rotates on the retina, a rotation equal and opposite to that of the eye. Therefore, the sensory effects of eye movements can also be predicted, to some extent, by a modal emulator. (This is only true to the extent that we ignore the visual periphery, and changes in resolution and color due to a non-uniform distribution of photoreceptors.) This is the sort of prediction that Duhamel et al. (1992) found in monkey parietal cortex.

Now, these are just special cases of object manipulation and self-motion. As soon as we generalize even slightly, we come up against sensory aliasing.

When an object is rotated about any axis other than the line of sight, its image on the retina deforms because of the laws of optical projection, and undergoes other changes because previously occluded parts come into view. These deformations cannot be predicted from motor commands coupled with sensory data alone; knowledge of the three-dimensional structure of the object (the deep parameters) is required. The relationship between manual rotations in depth and corresponding mental rotations was studied by Wohlschläger and Wohlschläger (1998).

As soon as the head moves (and it does so nearly all the time, unless one's teeth are clenched around a bite bar), the eyes no longer just rotate, but undergo translations as well. This leads to motion parallax, and again the changes on the retina can be predicted only if one knows the three-dimensional layout of the environment. (Interestingly, motor action seems to play a special role in this process – see Wexler et al. 2001.) Hence, Grush's "white cube" example in section 4.4 is incomplete: Moving sideways while facing a cube leads not only to a shift of the retinal image (as would be the case for an eye rotation), but also to a deformation, a deformation that can only be predicted if one knows the three-dimensional shape of the object (a solid cube, rather than an infinite set of other objects compatible with the initial sensory data).

So situations in which modal prediction is even possible appear, at best, as special cases of much more widespread situations in which sensory aliasing precludes any possibility of predicting sensory states from other sensory states. It would be strange, therefore, if a modal prediction mechanism existed just for those special cases, only to be superseded by a much more general amodal predictor as soon as one steps out of the special case. By parsimony, we might suppose that all predictors are amodal.

Another significant distinction to make is between motor and environment emulators. Grush begins with motor emulators – ones that predict, modally or amodally, the results of one's own action – but winds up with something he calls "environment emulators," the much more general task of which is to predict changes in the environment that are due not only to the subject's own action, but to all relevant forces. Now, it might be argued that motor prediction is very special, in that one has intimate, before-the-fact knowledge of forces and goals. Indeed, the dynamic properties of the predicted trajectories of objects that one manipulates seem to be quite different from those of objects one merely observes (Wexler & Klam 2001).

The main difficulty is how the environment emulator would articulate with the motor emulators described in the first part of the target article. Indeed, it is not easy to see how the precise and well-documented mechanisms of forward models, Kalman filters, and so on, are to apply to the environment emulator. What does the environment emulator share with the motor emulator, other than the general concept of prediction? The answer to this question might prove quite interesting. For instance, it *could* turn out that to predict and to imagine changes in external objects independent of one's own action ("motion-encoded" prediction, to use Kosslyn's term), one nevertheless has to "imagine" acting on the objects on some level. In this case, the activation of the motor system would not rise to the level of consciousness, but would result in the activation of the motor predictor. However, without such a motor implication in the prediction and imagination of external events, it is hard to see how one can make the leap from motor to environment emulators.

https://doi.org/10.1017/S0140525X04490098 Published online by Cambridge University Press