input, *reafference and all.* Thus, it is possible to predict reafference by subtracting the output of the amodal emulator from that of the modal emulator (see Fig. 1). In this schema both emulators can be continually recalibrated via Kalman filters.

3. Neural correlates of Grush's formulation? It is widely accepted amongst neurophysiologists that hindbrain structures such as the cerebellum and torus semicircularis are involved in the calculations of efference copy from the corollary discharges arising as a result of "motor" activity (Bell et al. 1983; 1997; Bodznick et al. 1999; Quaia et al. 1999). Although Grush does not deny this well-established wisdom, we feel that it would be helpful to the field if he would try to speculate, even at the risk of getting it wrong, about the hindbrain-midbrain-forebrain connectivities that would be required by his schemata, if it is correct that the cerebellum (and hindbrain adnexa) is the site of the efference copy (reafference) calculation. We feel that such an exercise, fraught with potential errors as it may be, could prove a useful antidote to the current philatelic fashion of looking with functional magnetic resonance imaging (fMRI) for some "new" area in the cerebral cortex that is associated with a particular function. It seems unlikely to us that restricting attention to the forebrain will enable us to come to grips with the organizational principles that must underlie the subtle, integrated calculations of ex-afference and reafference considered here.

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Duality's hidden influences in models of the mind

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Abstract: Dualistic approaches to the mind-body relationship are commonplace; however, the adoption of dualistic thinking can often obscure aspects of the way the organism functions as a whole biological entity. Future versions of the emulation theory will, it is hoped, address some of these issues, including the nature of process noise, how distinct iterations can occur, and how to deal with non-emulated aspects of motor control.

The purpose of Grush's target article is to "introduce and articulate" the emulation theory. I wish to mention some obstacles that emulation theory will need to work on which I believe are clouded by the mind-body dualism inherent in the theory. Pointing out some of these seemingly unconnected consequences provides opportunity for clarification and adjustment in future versions of the emulation theory of the mind. I also wish to clarify a point regarding the potential rejection of the emulation theory.

The nature of process noise. In the emulation theory, "process noise" refers to anything causing deviations between actual body position and emulated position. Because body is affected by noise, but mind runs its emulation separately, sources of noise are considered completely unknowable and can only be guessed post hoc when states are compared by the Kalman filter (KF) at a later point in time. This seems unproblematic when one accepts a simplistic mind-body dualism (with its analogous ship/crew relationship), but there are important aspects of the information carried by afferent nerves which it misses. The body continuously sends signals to the mind not only regarding its position and how it got there but also on what affected it. Causes of noise (external effects not anticipated at the start of motion) are often knowable and behave predictably.

Let us say that I reach for a glass on a boat and that an unanticipated wave begins to lift the ship as I start my reach, introducing noise. Because of the plasticity of my joints, my hand will momentarily be moving too low (as the ship rises the cup rises, but inertia prevents my hand from rising as much). If the KF adjusts for this, it will tell my arm to raise my hand, but as the wave passes, the ship will lower below its initial condition, causing my hand to go well above the cup through over-correction. The emulator is in luck, however, as other parts of the sensory system should send the mind information as to the nature of the noise it is experiencing (from afferents in my feet feeling the upward push of the hull to my inner ear registering the tilt it produces). The wave, although unanticipated, is relatively predictable in effect, and the mind can adjust behavior accordingly and still successfully grab the glass. I believe that most sources of "process noise" could be thus dealt with to a beneficial degree, as large amounts of "noise" are often predictable from minor initial variation. This aspect of control could be missed by thinking of the body as a ships' hull or the mind as a robotic arm control.

Perhaps a combination of the proposed "environment emulator" with the motoric emulator would start to address this issue. Unfortunately, interaction amongst emulators (or whether there are multiple emulators vs. one giant emulator) was not discussed in the target article. Further discrimination of pragmatically different types of noise may also be useful. In either case, I do not believe that would solve the problem completely.

Emulation as an iterative process. The KF performs its functions through a series of discrete "measures" taken from the afferent nerves (both those involved in the motion and those of other senses) when a given time step has past. This is used to estimate the current accuracy of prediction and to attune the filter to the current situation. The KF learns over time, adjusting its gain and calibrating the strength of muscles, flexibility of joints, and so on. The converse of this, of course, is that the body receives signals from the mind in an intermittent manner, adjusting what it is doing only when the mind's KF completes a new comparison, determines the most probable act of correction, and sends the next efferent signal to the body. Clearly, this type of thinking is possible only if the body is one thing and the mind is another thing altogether. But without a suggested mechanism of discrete sampling, one might suspect that feedback must be continuously flowing in both directions, and that both the body and mind were physical components of a single organism. Can the KF model be extended to produce continuous feedback? How would that influence our interpretations of these models or how we build robots/simulations to test them? Also, without requiring a description of a physical instantiation of the KF (see "Cautionary Rejection" below), how would our interpretation of the KF be affected if we viewed it as present in the physical structure of the mind, that is, if we were forced to reject dualism and its accompanying references to mental imagery?

Non-brain mechanisms of adjustment. A final thing that mind-body duality can obscure is neuronal non-brain mechanisms for maintaining and adjusting behaviors. These include feedback loops through the spinal cord, perceptual adjustments to detect sources of noise or gain information which could permit more accurate emulation (such as pupil dilation and analogous auditory adjustments), and so on. There are also a host of non-neuronal bodily adjustments which affect behavior such as hormonal changes and depletion of energy reserves and oxygen supply in local muscular regions. Certainly an emulation could not incorporate many of these, as many of them are activated only by things that would qualify as "process noise" and are therefore unpredictable. Also, many of them act in shorter times than required by the emulation theory (which Grush indicates is approximately 1 second). Are these mechanisms simply not deemed part of motor control? Does simple motor control not require an emulator? An affirmative answer to either question does not seem to mesh well with the emulation model, yet they are clearly implied by the use of dualism.

Cautionary rejection. As a final note, I am concerned with Grush's suggestion (with slight variations in wording in different

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places) that "As for what [sorts of] evidence would count against the emulation framework's applicability to [a domain such as] motor control, it is whatever evidence would count against [the specific model or theory that he is discussing at that time]" (sect. 2.6, para. 3). In these cases, he seems to be using the validity of the particular KF he cites as the only possible validity for an emulation theory of the mind more generally. This is both a brash move on his part (which I applaud) and not particularly historically accurate. It should be clear from the above comments that KFs are at best a highly useful (in the sense of generating novel scientific research) metaphor for how the brain is operating. The target article admits both that there are many different KF models and that necessarily, "the emulation framework relaxes the strict requirements of the Kalman filter" (sect. 2.4, para. 6). Other researchers may support different views of emulation (and if they do not now, certainly they may in the future). These others would certainly not want their opinions rejected if the KF is rejected. More realistically, progressive research programs often modify their predictions. And as Lakatos (1970, p. 151) amply stated: "To give a stern 'refutable interpretation' to a fledgling version of a programme is a dangerous methodological cruelty. The first versions may even 'apply' only to non-existing 'ideal' cases."

This seems to me the position of a strict KF model of the mind. Certainly it will go through adjustments and changes and, it is hoped, continue to make novel predictions at each stage. I see no reason why future versions of emulation theory could not find solutions to the problems I have pointed out, and I hope that I may look forward seeing them try.

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Although I have avoided a competitive approach, the criticisms presented here are inspired by James Gibson's (1966) approach to understanding perceptual systems, which attempts in its own unique way to deal with these issues.

Epistemology, emulators, and extended minds

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Abstract: Grush's framework has epistemological implications and explains how it is possible to acquire offline empirical knowledge. It also complements the extended-mind thesis, which says that mind leaks into the world. Grush's framework suggests that the world leaks into the mind through the offline deployment of emulators that we usually deploy in our experience of the world.

Grush endorses Kosslyn's claim that when we perceive something in the world we are running an online emulator that fills in information on the basis of expectations. We can then use efference copies of motor commands to run the emulator offline. This continuity between online and offline emulation explains the following epistemological puzzle. You go into a room and see a partially completed jigsaw puzzle on a table. You look at the puzzle and leave the room. You then mentally rotate one of the pieces and discover where it fits. You have now discovered something new – where the piece fits into the puzzle. I think you have discovered it by performing an inner analogue of an operation that, if you had performed it in the world, would have given you an empirical discovery and that also gives you an empirical discovery when you perform it in your mind, even though, in this case, you did not have access to the puzzle.

We can certainly perform such rotations, as R. M. Shepard and associates showed in a series of classic experiments (Cooper & Shepard 1973; Shepard & Metzler 1971). And the operations give us knowledge: We acquire knowledge by seeing things all the time, most obviously through our straightforward recognition of things in the world. The intuition that we need to overcome is that you derived the knowledge inferentially, *from what you already knew.* So suppose that, rather than leaving the room, you rotate the piece manually and discover where it fits. This is straightforward empirical discovery. From an epistemological point of view, rotating the piece mentally is no different from rotating it manually – in both cases you do not know where the piece fits until you have performed the rotation. Whatever we say about one we will have to say about the other. The physical case is an empirical discovery that is not derived from previous knowledge. Consequently, the mental case is an empirical discovery that is not derived from previous knowledge. What is unusual about it is that you perform it offline, when you do not have access to the puzzle.

I think this can be explained in terms of Grush's emulator framework. Grush says that perception involves "a content-rich emulator-provided expectation that is corrected by sensation" (sect. 6.3.1). The imagination (by which I mean our ability to form and manipulate images) uses the same emulator to provide similar content, now driven by efference copies of motor commands. In the case of the jigsaw puzzle, we run the emulator online when we rotate the piece manually and we run it offline, using efference copies, when we rotate the piece mentally. When content and copy are veridical, this offline emulator gives us empirical knowledge of the external world.

Now to extended minds. Andy Clark and Dave Chalmers (Clark 2003; Clark & Chalmers 1998) have recently argued that mind extends into the world through the use of "cognitive technology" or "mindware." It extends through *cognitive processes* when we use pen and paper to work something out, or when we use a computer, or even when we use language, which Clark thinks was the first technology. And it extends when we use physical objects, or even data structures such as encyclopaedias or CD-ROMs, as *external memory stores*, which we can consult "as needs dictate" (the phrase is Clark's).

Clark's and Chalmers' driving intuition is that if something counts as cognitive when it is performed in the head, it should also count as cognitive when it is performed in the world. We now have a natural complementarity, because my epistemological gloss on Grush's framework says that if a process gives us an empirical discovery when it is performed in the world, it will also give us an empirical discovery when it is performed in the head. This is in keeping with the spirit of the extended-mind thesis, because it erodes the skin-and-skull barrier between mind and world. But we can fill out the framework even more. Clark and Chalmers say that we use objects and data structures in the world as external memory stores. I think there is a complementarity here as well, inasmuch as we have inner analogues of external objects, which we carry around in our heads and consult as needs dictate.

Why do I think we have inner analogues? First, there is the question of symmetry. We perform cognitive actions in the world, and we perform actions in our heads that we would normally perform in the world. We also use the world as an external data store. If the symmetry carries over, we will have inner analogues of external data stores. Next, the problem with using external objects as memory stores is that they are not portable. Inner analogues, which we could carry around in our heads, would free us from this limitation. But more important, there is this: If we perform operations that we would normally perform in the world, on objects that are not present to our senses, then we must have inner analogues of those objects to perform the operations on. Consider the case of the jigsaw piece when we leave the room. We perform an operation in our minds that we would normally perform in the world. We say, loosely speaking, that we rotate the piece in the imagination. But what do we really rotate? The answer has to be: an inner analogue of the piece. As with the external piece, we can consult this inner analogue as needs dictate. We have remembered knowledge about the piece, so sometimes we will retrieve this remembered knowledge. But sometimes we will retrieve *non-*

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