

tual, motor, and conceptual processes in a common theoretical framework. Along with influential proposals by Damasio (1989), Barsalou (1999), and others, Grush is making a strong case for the importance of on-line and off-line simulation. His emulation theory extends previous work by emphasizing the role of efference copies and on-line, dynamic use of the feedback information. Further, he precisely specifies the characteristics of the control process and proposes some possible neural mechanisms. In our commentary, we focus mostly on the unique conceptual gains offered by the proposal, and highlight its fit to empirical data. However, we also suggest that more work is needed for the theory to achieve a respectable level of neurological plausibility.

Grush builds his main arguments around the motor system. Although the traditional simulation theories all highlight the general correspondences between the mechanisms underlying motor imagery and motor execution, the emulation theory, with its emphasis on on-line, efferent feedback, offers a more precise account of empirical data. This can be illustrated with a study that investigated the temporal relation between the physical and visualized performances of springboard dives (Reed 2002a). The study included participants across three skill levels (novice, intermediate, expert) and measured performance of different components within a dive (e.g., approach, hurdle). This design allows for a test of different predictions offered by the simulation and emulation accounts. The traditional simulation theory predicts that skill differences should manifest themselves only during the *first component* of the dive, during motor program selection. In contrast, emulation theory predicts that the skill differences continue throughout *all stages* of the dive, because the emulator would assess the consequences of each motor program selection as dives progress. Specifically, experts should use emulator corrections of their motor execution less because their motor programs are highly accurate and their selection is largely automatic. Novices cannot use the emulator for fine corrections because they simply lack motor programs with which to correct the errors. However, intermediates use the emulator the most to correct their selections of motor programs. The empirical data are consistent with emulation theory. Intermediate performers not only were comparatively slowest in the visualizations, but also showed predicted skill differences throughout the dives. Thus, emulation theory provides insight into the mechanisms underlying complex motor-skill imagery.

The gains offered by the emulation theory extend beyond the motor system. This can be illustrated by research on "embodiment" of emotion processing. Grush offers a useful idea that the "visceral/emotional emulator" helps not only in off-line processing (e.g., providing efferent feedback based on past decisions), but also in on-line processing of emotional material. Several findings not only support this general notion, but also highlight that the emulation process can be impaired on the "brain" level as well as the muscular level. Adolphs et al. (2000) observed that damage to right somatosensory-related cortices impairs recognition of emotion from facial expressions. Niedenthal et al. (2001) showed that participants required to hold a pen in their mouth (blocking efferent feedback) performed worse at detecting changes in emotional facial expression than participants allowed to mimic the expressions freely. Finally, a provocative study discussed by Zajonc and Markus (1984) found that participants who watched novel faces while chewing gum (motor-blocking condition) later performed worse on a recognition test than either participants who encoded by mimicking faces (muscular-facilitation condition) or participants who squeezed a sponge (motor-control condition). This finding is particularly important for the emulation theory because it shows that to benefit cognition, the emulator needs feedback from a specific effector, not just any sensory feedback.

There are many more findings like the ones just mentioned. In fact, a recent review of the social-psychological and emotion literature revealed a number of phenomena that can be explained by the ideas of simulation (emulation) and embodiment (Niedenthal et al., in press). In short, theories such as Grush's, as well as Barsalou's and Damasio's, offer much promise not only when it comes

to accounting for specific problems in motor control, imagery, or emotion, but also as general theories of cognition, including social and emotional cognition.

However, to take advantage of the potential explanatory power of emulation theory, research must clarify how emulators are neurally instantiated. Grush ventures that the emulator for his prototypical system, the musculoskeletal system (MSS), is contained in the cerebellum. Since Grush's theory explains imagery to be a product of emulation, this proposal predicts that damage to the cerebellum would disrupt motor imagery. However, in contrast to lesions in other brain regions such as the striatum, frontal lobes, and parietal lobes, cerebellar lesions are not known to induce deficits in motor imagery. For example, patients with Parkinson's disease show selective deficits on motor imagery tasks, but patients with cerebellar atrophy do not (Reed & O'Brien 1996). This suggests either that emulation is not necessary for imagery or that there is more to MSS emulation than the cerebellum. In general, we suggest that emulators may not be discrete structures, but instead, capitalize on multiple subsystems of the brain.

In sum, emulation theory moves us beyond the current simulation theories by providing more mechanistic explanations and specific predictions. In its emphasis on the critical role of efferent feedback in efficient processing, emulation also gives current theories a good functional reason for why perception, cognitive, and motor systems are so tightly intertwined. Despite these strengths, the neural instantiation of such an emulator must be developed further so that it can incorporate multiple cognitive and motor functions. Further, the emulator, rather than being its own module, should be conceived as a general brain mechanism that permits feedback to multiple existing neural systems that have more or less direct relationships to the motor system. In short, the emulation theory requires some additional development before it fully filters down from armchair to laboratory.

Emulation of kinesthesia during motor imagery

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Abstract: Illusory kinesthetic sensation was influenced by motor imagery of the wrist following tendon vibration. The imagery and the illusion conditions commonly activated the contralateral cingulate motor area, supplementary motor area, dorsal premotor cortex, and ipsilateral cerebellum. This supports the notion that motor imagery is a mental rehearsal of movement, during which expected kinesthetic sensation is emulated by recruiting multiple motor areas, commonly activated by pure kinesthesia.

It is uncertain whether motor imagery could generate expected kinesthetic sensation, although it has been considered a mental rehearsal of movement. It is empirically known that many people can experience vivid motor imagery, mostly involving a kinesthetic representation of actions (Feltz & Landers 1983; Jeannerod 1994; Mahoney & Avenier 1987). In movement control, the musculoskeletal system is subject to the measurement of proprioceptive and kinesthetic information generated by actual movement and relayed as feedback sensory signals. One of the important predictions of Grush's "emulation theory" in motor imagery is that the emulator will output the sensory signal in "mock" proprioceptive format in response to motor control signals (efferent copy), resulting in kinesthetic sensation. This is in contrast to the "simulation theory" in motor imagery, in which only efferent copies are supposed to be generated. If the emulation theory is correct, one may identify the output sensory signals generated by the emula-

The art of representation: Support for an enactive approach

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Abstract: Grush makes an important contribution to a promising way of viewing mental representation: as a component activity in sensorimotor processes. Grush shows that there need be no entities in our heads that would count as representations, but that, nevertheless, the process of representation can be defined so as to include both natural and artificial (e.g., linguistic or pictorial) representing.

Grush helps banish the misleading practice of viewing "representations" as static entities, and of using "representation" as an object term like "picture" or "imitation," as in "That picture is not an original Rembrandt, it's an imitation." Grush's theory shows that the term refers to a process. Nothing is "a representation" except as a part of that process, and even then the usage is ambiguous. Think of representation as the process of representing, and of a particular case as an instance of representation; but never think of that instance as "a representation." I predict that if we are successful at reconceiving representation so that the latter usage becomes technically meaningless, then representation will no longer be a philosophical problem.

Humans are skilled at the art of representation, socially and aesthetically, and traditionally their products are called "representations." (Grush himself employs that usage at times.) People who are successful create an object that produces in the perceiver a state similar in desired ways to that of perceiving what the artist is representing. In itself, there is no harm in calling the products "representations"; the harm comes when the source of these objects is ignored, and one looks for some feature of the objects *themselves* that makes them representations. Physical resemblance is one obvious candidate. The most dangerous view, for purposes of philosophical clarity, is holding that a natural mapping from the "representations" to the worldly objects they represent exists through causal relations between representations and objects. In natural language, words "represent" objects through the relation between the objects and the learning of the words. Language has become the paradigm for representation for many philosophers, to the extent that many theorists derive the nature of mental representations from that of natural language. There are well-known problems with this approach to representation and no generally accepted solution; this path leads to a dead end.

But representation is a real phenomenon. If it is a process, then we should seek the paradigm in human activity. I (Newton 1996), along with many others (Grush mentions some, e.g., Johnson-Laird 1983; Lakoff 1987), hold that representation is based in human behavior and perception. The general theory is simple to state in terms of motor control systems. An alternative to pure feed-forward or feedback systems is one in which the final goal state is *emulated* by a mechanism allowing the system to perform its goal-directed actions in a type of *rehearsal* of the decisive final actions, for fine-tuning, without commitment to a final outcome. Grush's proposal is that a mechanism for signal processing, the Kalman filter, performs this function. We can say that in using the Kalman filter the motor system is representing its goal.

Note that it is not obvious what would constitute "a representation" in this proposal. The Kalman filter is not a representation but a mechanism that allows representational activity by providing, among other things, appropriate isomorphism with the goal state. We could say that the Kalman filter, together with the motor-control system that employs it, constitutes a representation of the action in the static sense, but that would be inaccurate because the combined system as a whole is related to the goal action only when employed in the *process* of preparing for the final action. If we want to call that system a representation, then representations are much more ephemeral things than the language paradigm would suggest, and the philosophical interest in representations as

entities would lose its motivation. It is much more useful to take the motor-control system as a whole as a basic example of representational *activity*, because that will allow us to define "representation" in a firm, noncircular manner:

Representation is the process of performing goal-directed activity in a manner that allows the activity to be rehearsed and optimized in advance of the realization of the goal. This realization (whether planned or simply hypothesized) is what is represented by the activity.

Note that this definition includes the representational activity involved in perception, as Grush intends. He argues that perception involves anticipation of sensory input (sect. 5.3). With perception, the goal is the interpretation of sensory input, and the emulation system functions for that purpose as it does in the case of purely motor activity. This approach, holding that imagery constitutes anticipation of actual perception, has been proposed by Ellis (1995). Here again, Grush's detailed account of the mechanism of the Kalman filter provides both support and testability.

The discussion of mental imagery is important because mental images have borne much of the weight of the representation-as-entity approach. Grush shows how mental imagery can be seen as a truncated or constrained version of representational activity, in which (using the Kalman filter) environmental sensory input is discounted and the representing process is "an off-line operation of an emulator" (sects. 4.4 and 4.5). Sensory input is replaced by internally generated input, and the initiating motivation is not actual perception but what Ryle (1949) would call "pretending" to perceive objects, knowing that one is not really perceiving them.

Conclusion. Of course the brain mechanisms for representation do not constitute art; they are natural and probably unconscious. But it is useful to see that artistic activity – creating representational objects for the purpose of inducing desired states in observers – can be understood as constituting the same functional activity as the motor paradigm. The artist, instead of presenting the viewer with a vase of flowers, allows the viewer to "rehearse" the activity of looking at a vase of flowers with a particular focus and affective response. Thus, the artist and the viewer are both engaged in representational activity. To say that the painting *itself* represents a vase of flowers can be a shorthand way of referring to the process, but unless this process is understood, in the way Grush has offered or in some similar way, as representation in the active sense, we will continue to wonder how one physical object can bear such a profound relationship to another physical object, with no visible connections and all by itself.

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Emulation theory offers conceptual gains but needs filters

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Abstract: Much can be gained by specifying the operation of the emulation process. A brief review of studies from diverse domains, including complex motor-skill representation, emotion perception, and face memory, highlights that emulation theory offers precise explanations of results and novel predictions. However, the neural instantiation of the emulation process requires development to move the theory from armchair to laboratory.

There is currently much interest, within psychology and cognitive science, to develop theoretical frameworks that integrate percep-

tor by detecting their interaction with pure kinesthetic sensation without movement.

It is known that pure kinesthesia without movement can be elicited by vibration of the tendon with a specific frequency (83 Hz; Craske 1977; Goodwin et al. 1972a; 1972b; Naito et al. 1999). Using this fact, Naito et al. (2002) showed that motor imagery affected pure kinesthetic sensation, generated by tendon vibration without overt movement. They found that the motor imagery of palmar flexion, or dorsiflexion of the right wrist, psychophysically influenced the sensation of illusory palmar flexion elicited by tendon vibration. Motor imagery of palmar flexion psychophysically enhanced the experienced illusory angles of palmar flexion, whereas dorsiflexion imagery reduced it in the absence of overt movement. This finding indicates that the emulator, driven by the mental imagery, outputs the "mock" sensory signals in a proprioceptive format, which interferes with the real (but artificially generated) proprioceptive sensory information from the musculoskeletal system.

Another prediction of Grush's emulation theory is that the articulated emulator is a functional organization of components (articulants), whose interaction is comparable to that within the musculoskeletal system, and hence their neural representations are expected to be common. This point was also demonstrated by the study of Naito et al. (2002). Regional cerebral blood flow was measured with O-15 labeled water ($H_2^{15}O$) and positron emission tomography in ten subjects. The right tendon of the wrist extensor was vibrated at 83 Hz (ILLUSION) or at 12.5 Hz with no illusion (VIBRATION). Subjects kinesthetically imagined doing wrist movements of alternating palmar and dorsiflexion at the same speed with the experienced illusory movements (IMAGERY). A REST condition with eyes closed was included. The researchers identified common active fields between the contrasts of IMAGERY versus REST and ILLUSION versus VIBRATION. Motor imagery and the illusory sensation commonly activated the contralateral cingulate motor areas, supplementary motor area, dorsal premotor cortex, and ipsilateral cerebellum. The researchers concluded that kinesthetic sensation associated with imagined movement was generated during motor imagery by recruiting multiple motor areas, which were also activated by the kinesthetic sensation generated by tendon vibration. These commonly activated areas may constitute the articulants of the emulator driven by the efferent copy during motor imagery.

In conclusion, generation of kinesthetic sensation during motor imagery, and its neural representation common to kinesthesia without movement, can be interpreted as "emulated kinesthetic sensation" in the framework of the emulation theory by Grush.

Modality, quo vadis?

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Abstract: Grush's emulation theory comprises both modality-specific and amodal emulators. I suggest that the amodal variety be replaced by multisensory emulators. The key distinction is that multisensory processing retains the characteristics of individual sensory modalities, in contrast to amodal processing. The latter term is better reserved for conceptual and linguistic systems, rather than perception or emulation.

Grush develops his emulation theory as a unified account of perception, imagery, and motor control, with the prospect of extension to diverse other neural functions. This theory is an advance over previous, less systematic formulations of simulation and imagery as being important in sensorimotor function. It makes the claim that particular neural elements work together in an emulation of perceptual or motor tasks, running in a special mode in which they are disconnected from external inputs/outputs. Vari-

ous emulations differing in their characteristics can hence be run, based on which the organism can select the best one to implement in interaction with the environment. The appeal of the theory stems from its unifying potential, and hence its success will be measured to a large extent by how well its binding of seemingly disparate streams of thought bears up over time. In this commentary, I focus on the relationship between the proposed sensorimotor emulator and sensory modality.

Grush argues for modality-specific as well as amodal emulators in the nervous system. Modality-specific emulators are relatively easy to understand, in terms of the operation of modality-specific sensory or motor systems. For instance, the findings reviewed in section 4.3 of the target article are compatible with a role for a motor emulator during visual imagery. However, the concept of a strictly amodal emulator, one that is entirely independent of any sensory "tags," is less clear.

Let me make it absolutely clear that I am not arguing against amodal representations in the brain. Such representations must exist for abstract concepts that can be encoded linguistically, or "propositionally," rather than directly in the workings of sensory systems. Indeed, as a vital part of human thought and communication, they are among the most important abilities that evolution has conferred on our species, compared to the other species that live or have lived on this planet. It is the characterization of abstract, amodal representations as imagery, and, by extension, as substrates of emulation strategies, that I am not comfortable with. Rather than "amodal" emulators, I suggest invoking "multisensory" emulators to provide the link between modality-specific systems and between these systems and abstract representations. I must emphasize that this is not a merely semantic distinction. By "multisensory," I mean a system that receives inputs from more than one sensory modality. The existence of multisensory processes is well established, as is their neural implementation. The functions of multisensory processing include integration between the senses, cross-modal recruitment of sensory cortical regions, and coordinate transformation. Each of these functions has been studied in some detail.

Coordinate transformation in multisensory neurons of the posterior parietal cortex (PPC) has been intensively studied by Andersen and colleagues. This work indicates that multiple reference frames are represented in different regions of the PPC (Buneo et al. 2002; Cohen & Andersen 2002; Snyder et al. 1998). Reference frames may be allocentric, as in Brodmann's area 7a; eye-centered, as in the lateral intraparietal area (LIP) and parietal reach region (PRR); body-centered, as in LIP; and both eye- and hand-centered, as in Brodmann's area 5. Further, the eye-centered neuronal responses in LIP and PRR are gain-modulated by a variety of other factors such as eye, head, body, or hand position (Cohen & Andersen 2002). This effectively allows for a distributed representation of multiple reference frames simultaneously, and hence, for the coordinate transformations that are required for particular tasks, for example, between the retinocentric reference frame of visual stimuli or the head-centered reference frame of auditory stimuli and the body-centered reference frame of reaching arm movements, so that motor outputs may be appropriately directed. Multisensory emulators, then, could be engaged for specific coordinate transformations to allow planning of motor behavior as dictated by the organism's current goals.

Another function of multisensory neurons is to integrate perceptual processes across the different senses. Such multisensory integration has been studied at the level of single neurons in the superior colliculus (Stein & Meredith 1993) and more recently in human cerebral cortex using functional neuroimaging. A case in point is the integration of auditory and visual information during perception of speech, which appears to depend importantly on cortex in the superior temporal sulcus (Calvert 2001). Moreover, Freides (1974) suggested three decades ago that, regardless of the modality of sensory input, the task at hand, especially if it is complicated, will recruit the sensory system that is most adept at the kind of processing required.

One means of such cross-modal recruitment is imagery. For instance, visual imagery may accompany tactile perception and could play a role in the engagement of visual cortical areas during tactile perception. Such recruitment of visual cortex has now been demonstrated in a variety of tactile tasks involving perception of patterns, forms, and motion, and appears to be quite task-specific, with areas that are specialized for particular visual tasks being recruited by their tactile counterparts (Sathian et al. 2004). An alternative interpretation of this type of cross-modal sensory cortical activation is that the regions involved are truly multisensory rather than unimodal. There is, in fact, increasing evidence that cortical regions traditionally considered to be unimodal are actually multisensory, receiving projections from other sensory systems in addition to their "classic" sources (e.g., Falchier et al. 2002; Schroeder & Foxe 2002). Multisensory emulators could clearly be employed to facilitate such cross-modal recruitment and synthesis.

My point is that, in all these examples of multisensory and cross-modal processing, specific modality tags appear to accompany the relevant sensory representations, which are associated with corresponding coordinate systems. This differs from Grush's account, in which there is an amodal system, devoid of specific modality tags, that is used for perception and for internal emulation. I suggest that such amodal, propositional systems are conceptual and linguistic rather than being perceptual or the substrate for either imagery or sensorimotor emulation. It will be important for future empirical and theoretical research to attempt to distinguish clearly between multisensory and amodal neural systems.

Brains have emulators with brains: Emulation economized

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Abstract: This commentary addresses the neural implementation of emulation, mostly using findings from functional Magnetic Resonance Imaging (fMRI). Furthermore, both empirical and theoretical suggestions are discussed that render two aspects of emulation theory redundant: independent modal emulators and extra measurement of amodal emulation. This modified emulation theory can conceptually integrate simulation theory and also get rid of some problematic philosophical implications.

Emulators with brains. The emulation account provides a formal way to apply the idea that the brain's default mode is not passive waiting but active prediction, not only in motor control and imagery, but also in perception and perceptual imagery – an extension which fits perfectly with a long series of fMRI studies we performed on voluntary anticipatory processes. These studies made use of the serial prediction task, which requires participants to predict perceptual events on the basis of stimulus sequences. The lateral premotor cortex (PM), pre-supplementary motor area (pre-SMA), and corresponding parietal/temporal areas are engaged in active anticipation of sensory events. Note that this network is activated in absence of motor behavior, and that perceptual input is controlled by contrast computation.

Several functional characteristics of the considered areas render them candidate components of an emulator network. First, in the aforementioned studies each PM field's response is restricted to specific stimulus features: PM fields for vocal movements are engaged in rhythm and pitch prediction, those for manual movements, in object prediction, and those for reaching and pursuit, in spatial prediction. A simplified synopsis of the results indicates that the anticipation of sensory events activates the PM fields of those effectors that habitually cause these sensory events (Schubotz & von Cramon 2001; 2002; Schubotz et al. 2003). This

"habitual pragmatic body map" (Schubotz & von Cramon 2003) in PM may precisely reflect Grush's description of an "articulated" body/environment emulator. Second, our findings would also be in line with an emulation network that entails both amodal and modal representations.

Grush proposes motor regions to reflect the controller, and ventral and dorsal processing streams to be the core environmental emulator. We would rather suggest that multiple PM-parietal loops (including the ventral/dorsal stream) function as emulators, with each loop linking both heteromodal and unimodal representations (following the terminology in Benson 1994). One may even hold articulated emulation to be the default mode of PM-parietal loops which are exploited for perception, action, and imageries (see Fig. 1). Visual, auditory, or somatosensory imagery might be generated by efferent signals to and feedbacks from the corresponding unimodal association cortices.

We argue that such a modal emulation cannot be considered to be independent from amodal emulation. Rather, the same signal is concurrently sent to both unimodal and heteromodal association areas, even though current internal and external requirements may then determine which feedback becomes causally effective. Visual, auditory, hand, and foot imagery may introspectively feel different possibly because the controller exploits different premotor-parietal-subcortical loops. But all these networks, first, are made of both unimodal and heteromodal cortices which, second, communicate with ease. Possibly this in turn renders an extra measurement process redundant, as we also argue. On the other hand, "controller" functions (or perhaps better, competitive filter functions) may be realized more restrictedly within pre-SMA, in turn under the influence of anterior median frontal cortices, lateral prefrontal cortex, and extensive feedback projections.

Don't introduce independent modal emulators – even if imagery sometimes feels purely visual . . . An introspectively compelling reason for suggesting independent modal emulation is that some kinds of modal imagery (e.g., a vase) feel purely visual and not at all motor. However, our fMRI findings reveal introspective reports to be unreliable (because introspection does not tell us that motor areas are engaged in non-motor anticipation). Likewise, we are introspectively blind to the empirical fact that perceiving an object includes perceiving what is potentially done with that object (see Gibson [1979/1986] for the notion of an object's affordance, and, e.g., Fadiga et al. [2000] for premotor responses to mere object perception in the monkey). Conversely, it is conceptually inconsistent to assume amodal emulators to be independent of modal emulators, because in the emulation account, perception is sensation, given an interpretation in terms of amodal environment emulators, whereas sensation in turn is the on-line running of modal emulators. It therefore appears that amodal and modal emulation have to be conceptualized as reciprocally dependent¹.

. . . And don't measure the emulators – even if imagery sometimes feels proprioceptive. An introspectively compelling reason for suggesting extra measurement is that motor imagery feels proprioceptive and not at all dynamic/kinematic. This also builds the core premise for splitting emulation from simulation: A motor plan is a dynamic/kinematic plan, whereas full-blown motor imagery is (mock) proprioceptive by nature and therefore must be previously transformed from the former by intermediate emulation and measurement.² However, exactly this premise would be rejected by accounts based on the ideomotor principle (e.g., theory of event coding; Hommel et al. 2001). These take motor acts to be planned in terms of desired action effects, that is, expected sensory events, and therefore plans and effects most likely share a common neural code. Comfortingly, emulation theory is not committed to the view that efferent signals are motor by nature. To be an efferent signal is nothing more than to be a delivered signal, no matter whether motor, sensory, sensorimotor, or amodal. Let us assume that the controller speaks "Brainish," the lingua franca spoken by every subsystem in the brain, and that "measurement" is nothing but (and therefore should be termed) feedback from