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Circulation as consciousness

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performance, training procedures, the composition of cardiovascular state, and what the monkeys actually did, it is difficult to assess alternative explanations. Engel's exercise contingency notwithstanding, it is possible that the pattern of motor behavior exhibited by the monkey differed between the exercise-alone and combined conditions, and that the exercise-alone pattern was accompanied by an increase in sympathetic arousal that eventuated in less efficient energy utilization under this condition. Sympathetic activation might have been triggered by exercise level (Robinson, Epstein, Beiser & Braunwald 1966) or released by behavioral contrast that could conceivably have been induced by the procedures of this study (single versus dual contingency) (Mackintosh 1974). Or, grouping of the exercise-alone sessions early in the study could have confounded habituation with training conditions. On the other hand, because the results are presented as changes from an unreported baseline, we cannot assess the alternate possibility that sympathetic drive might have been elevated throughout sessions using the combined contingency. This possibility exists because such training was more demanding and probably associated more often with shock than performance under other schedules, and because the conditions signalling this type of session were apparently present during the baseline period (Ainslie & Engel 1974). Sympathetic activation elicited by the task environment could have diminished the relation between changes in heart rate and oxygen consumption by elevating the prevailing heart rate and diminishing variability in the heart rate measure. These and other possible explanations need to be looked at because intrinsic mechanisms would be expected to oppose a diminished cardiac output in the combined condition when workload is held constant. Engel's interpretation implies that cardiospecific instrumental learning is powerful enough to counteract such mechanisms, but previous efforts to uncouple cardiovascular and somatic activities through biofeedback do not encourage optimism on this point (Brener 1983; Newlin & Levenson 1978; Roberts 1978).

Having said this, it should be noted that Engel's research on instrumental learning is unique for the length of training given. Conscious processing of action-outcome relations appears important in the early stages of visceral learning (Hughes & Roberts 1985), but how information accumulates with extended training is uncertain. I look forward to Engel's experimental reports with interest.

On the circulation as cognition

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Engel makes a strong case that modifications of an organism's circulatory status is an integral part of its behavioral system. The circulation is not merely reactive, it can also be anticipatory and adaptively conditional in response to available information. Assuming that Engel is right, this claim has important implications for cognitive science. My intention here is to reflect on the impact of the circulation's anticipatory adaptive features on our notions of cognition.

A number of individuals have thought it useful (or even critical) to distinguish cognitive from noncognitive behaviors (e.g., Pylyshyn 1984; Terrace 1982; cf. Roitblat 1982; Roitblat & Weisman 1986). Noncognitive behaviors were thought to be mediated by reflex or reflexlike systems on a fairly simple mechanistic basis. In contrast, cognitive behaviors were thought to be mediated by computational systems that operated on symbolic representations in a content-dependent manner. In particular, Pylyshyn (e.g., 1980; 1984) proposed a criterion of "cognitive penetrability" to distinguish between cognitive behavior and behavior governed by "functional architecture." Behaviors that can be explained only if we know the content of the information encoded are cognitive behaviors, whereas behaviors that can be explained directly in terms of the structure of the organism, its functional architecture, or how it is "wired," are noncognitive behaviors. Cognitive behavior is modified in rational ways by information-bearing modulating events, but noncognitive behaviors bear a fixed stimulus-response relationship that is uniform whatever content or meaning the stimuli might have. "If we can set up situations demonstrating that certain stimulus-response regularities can be altered in ways that follow these rational principles, we say that the input-output function in question is cognitively penetrable, concluding that at least some part of this function cannot be explained directly in terms of properties of the functional architecture; that is, not 'wired in' but requires a cognitive, or computational, or representation-governed explanation" (p. xvii). The circulation seems to meet this criterion of cognitive penetrability. At least some part of the circulatory function is, therefore, cognitively based.

For example, animals can proactively modify their heart rates in anticipation of a signal (e.g., Gottlieb & Engel 1979; Engel & Joseph 1982). What is perhaps more important, however, is that these same animals can modify their heart rates in opposite directions in the presence of the same signal, depending on the contingencies of reinforcement. Their responses are thus seen to be rational and conditional on information-bearing modulating events. Furthermore, humans show an attenuated ability to adjust their blood pressures while performing mental arithmetic (Brooks et al. 1978), indicating that the baro-adjusting response requires mental work effort or access to some of the same resources that are necessary to perform mental arithmetic.

A few years ago I argued that no principled basis was available for distinguishing between cognitive and noncognitive functions (Roitblat 1982). The apparent cognitive penetrability of the circulation system supports this claim. The brain can be nothing more than the changing patterns of neural activity and all information, whether about the danger of a situation or the status of one's blood pressure must somehow be encoded in terms of the location and/or rate of firing of neurons. What we typically think of as cognition emerges out of the organization and pattern of these firings, but there is no principled way to distinguish between those patterns that are cognitive and those that are not.

On an a priori basis, few functions of the body seem more biological and less cognitive than the functions of the circulatory system. If the criterion fails in excluding such a biological function as the circulation, it can hardly succeed in any interesting or useful manner. Even the circulatory system is controlled by representations and computational functions that are at least similar to those that control other cognitive functions.

Circulation as consciousness

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Latent in Sherrington's (1973) concept of the reflexes is the stipulation of their dissociability. Nevertheless, perhaps due to the forceful analysis of Cannon (1929), the idea that centrally controlled reflexes responded additively remained popular. Even though popular, this idea is not as prevalent today as it was 10 years ago. Indeed, in another time, Engel's essay would have been viewed as heretical. Perhaps even today, among some groups, the idea that physiological response systems are behavior and that they are dissociable (just as walking and talking at the same time are dissociable) remains untenable. And perhaps there are conditions in which Engel's analysis fails. However, my comments are intended to push the issue further, to consciousness. Perhaps the pattern of "reflexes" reflects and even directs experience. Perhaps changes in the circulation and the many permutations of dissociations are experience. Of course, this view owes its debt to the mentalistic reasoning of William James (1892), and its contemporary scientific extension to the Laceys (1974; 1959; 1967; 1970). The following brief review, coupled with the analysis of Engel, supports the cardiovascular role in consciousness.

Pressure sensitive receptors (baroreceptors) in the carotid sinus and aortic arch assist in homeostatic control of blood pressure. Baroreceptors increase their firing rates during transient blood pressure increases and decrease their rate as blood pressure falls. However, the baroreceptors have functions in addition to those classified as homeostatic. In 1929, Tournade and Malmejac found that stimulation of the carotid sinus nerve diminished muscle tone in anesthetized animals. Similarly, Koch (1932) found that increased pressure in the carotid sinus of a dog led to decreased motor activity and even prolonged sleep.

Bonvallet, Dell & Hiebel (1954) discovered that increased carotid pressure shifted electrocortical activity from low-voltage fast activity to high-voltage slow activity. Thus, when the baroreceptors in the wall of the carotid sinus detected increased pressure, the electrocortical activity was inhibited (an example of dissociation). Severing the vagus and glossopharyngeal nerves released the inhibitory influence.

Cells firing with a cardiac rhythm have been recorded in the medullary areas (Humphrey 1967; Smith & Pearce 1961), and coagulation in this region prolongs the effects of a stimulus. Lacey (1967) has suggested that the function of this area, rich with cardiovascular representation, may be to "control the duration of an episode of stimulus produced in the brain" (p. 27).

Evoked potentials in supramedullary areas (posterior hypothalamus) occur as early as 10 msec following stimulation of the carotid sinus (Adair & Manning 1975). When, in turn, these hypothalamic areas were stimulated, a 65% reduction in single-unit firing occurred in medullary neurons responsive to baroreceptor activation. Another supramedullary structure responsive to vasomotor activity is the locus coeruleus (LC). In a series of studies by Svensson (Svensson & Thoren 1979; Persson & Svensson 1981), blood was withdrawn (experimental hemorrhage) or fresh blood loaded into conscious rats. After blood loading (increased pressure) behavioral depression and inhibition of NE (norepinephrine) and neuronal firing rate was observed in the LC. Hemorrhage resulted in increased exploration and activation of NE and neuronal firing rate in the LC. Earlier, Coleridge, Coleridge & Rosenthal (1976) found that distension of the carotid sinus caused prolonged depression of activity of pyramidal tract cells in the motor cortex. Similarly, human spinal cord excitability has been shown to vary directly with the cardiac pulse. Forster and Stone (1976) demonstrated that the "physiological tremor" of normal skeletal muscles was a function of cardiovascular modulation, presumably via gamma-motor neurons. They speculated that the rising phase of systolic pressure might alter neuronal excitability by a piezo-electric effect on motor neuron membrane, or that neuronal firing rate was a function of microcirculatory, oxygen-carbon dioxide tension during the cardiac cycle.

An interesting problem is the extent to which "consciousness" may be coupled with circulatory logistics. For example, Thompson and Barnes (1979) and Thompson, Yates, Franzen & Wald (1983) have mapped rapidly responding venous afferents from femoral and brachial veins to the motor-sensory cortex of cats. Stimulation of forelimb and hindlimb venous afferents resulted in unique topographic distribution of the cortical evoked response. Where stimulation was applied in the circulatory system determined the cortical response. Thus, the circulation does not send simple, additive transmissions.

In addition to the physiological relationships described, the Laceys and others (Lacey 1959; 1967; Lacey, Kagan, Lacey & Moss 1964; Sandman, McCanne, Kaiser & Diamond 1977; Sandman & Berka 1982; Libby, Lacey & Lacey 1973; Cacioppo & Sandman 1978; Hare 1973), have indicated that transient decreases in blood pressure or heart rate improve attention, and increased heart rate facilitates cognitive elaboration. However, the relationship of the cardiovascular system to the electrical activity of the brain in human subjects has received less attention. The early report of Obrist and Bissell (1955) suggested that changes in posture compromised cerebral blood flow and were reflected in the EEG. Ingvar (1972) extended these principles and demonstrated that increased perfusion was related to increased arousal of EEG patterns. Callaway and Buchsbaum (1965) and Callaway and Layne (1964) demonstrated a synchronous relationship between the ventricular contraction of the heart and the "ascending" wave of the alpha rhythm.

In a series of studies (Walker & Sandman, 1977; 1982; Sandman et al. 1982; Sandman 1984), we have described the influence of transient changes in heart rate or pulse pressure on cortical event-related potentials (ERPs) in human subjects. In these studies we have found that during transient decreases in blood pressure, early components (i.e., 100–200 msec) of the ERP were enhanced. Furthermore, this effect was especially significant in the right hemisphere of the brain. These findings suggest that ERP components thought to be related to dimensions of consciousness covary with the cardiovascular system and are lateralized in the brain.

One conclusion implied by these findings is that a portion of environmental awareness is "hardwired." That is, inviolable relationships between the heart and brain may set limits on consciousness. There may be optimal, cyclic physiological "windows" for efficient interaction with the environment. Certainly, the data from these studies indicates that there are precise periods during the cardiac cycle when perception and the impact of stimulation are optimal.

What mechanisms could account for these findings? One possibility is that blood flow changes the conductivity of the brain. In this regard, Klivington and Galambos (1967) estimated that blood contributes 10% to the conductivity of the cortex. Another possibility is that metabolic changes increase neural efficiency. For example, Willison, DuBoulay, Paul, Russell, Thomas, Marshall, Pearson, Simon, and Wetherley-Mein (1980) reported that patients with elevated VH (venous hematocrit: increasing blood viscosity and decreasing cerebral flow) do poorly on simple tests of alertness. When the VH was lowered in these same subjects, performance improved.

A third possibility is the nature of neurogenic control of the vasculature. EVRs (evoked vascular responses), elicited by auditory stimulation in humans, were measured with the rheoencephalograph and adapted to ERP procedures (Sandman, O'Halloran & Isenhart 1984). Rapid responses were identified by statistical analysis during the diastolic but not the systolic phase. The latency of the EVR defied the time course of previously described vascular changes in response to altered metabolic activity. Thus, this response may be a neurogenically mediated vascular event in preparation for altered metabolic demand.

These possibilities fall short of the heretical views of Kennedy (1959), who proposed that synchronous brain activity was an artifact induced by the mechanical energy from the ventricular contraction of the heart (Bering 1955). This "pulse," applied to a gelatinous mass (the brain), in a limited, closed container (the skull) initiated and sustained brain activity via the cerebrospinal fluid. Consciousness, or the frequency of oscillation, was related to the "consistency" of the brain and modified by the cerebral vasculature. Thus, during attention, the brain was engorged with blood, detuning the oscillators and blocking synchronous activity. These possibilities are not mutually exclusive, and all support the radical neo-Jamesian proposal that the sea of consciousness rides on the oscillating waves of the cardiovascular system.

Vascular components of the orienting and defensive reflexes

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Cardiovascular responses are integral components of behavior. They can arise from innate genetic factors, they can be elicited by conditional stimuli, and they can be emitted in anticipation of consequences (Barry 1984; Sokolov 1963).

Parallel recordings of digital and head plethysmograms in man reveal the existence of an OR (orienting reflex) characterized by digital vasoconstriction and head vasodilatation. This OR selectively habituates with repeated stimulation and is restored by any change in the stimulus. A DR (defensive reflex) evoked by painful stimuli is marked by nonhabituating vasoconstriction in the head and hand. The time-course of the development of a classical conditioned DR in response to paired sequences of neutral and painful stimuli is characterized by two phases: (1) the initial restoration of the OR and (2) the gradual establishment of the DR accompanied by parallel OR habituation. At the beginning of the extinction of the conditioned DR, when the painful unconditional stimulus is no longer presented, the conditioned DR is followed by an OR induced by the absence of the painful unconditional stimulus.

Anticipatory vascular responses can be observed during conditioning when the painful stimuli are presented at constant intervals. The initial index of the anticipation is a conditioned OR preceding the unconditional DR. This expectancy OR is gradually followed by a time-dependent conditioned DR and the subsequent unconditioned DR and an OR evoked by the mismatch between the expected unconditional stimulus and its omission.

The dissociation between the OR and the DR under various conditions depends on parallel channels of command neurons (Kupfermann & Weiss 1978) coding vascular components of the OR and DR by the "lable line principle."

Circulatory behavior: Historical perspective and projections for the future

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Dr. Engel's perception that the circulation, as well as other visceral functions, is an integral part of an organism's behavior is important and illuminating. Although today the concept is not widely shared by medical and behavioral scientists, it is not new. One finds it implicit in Cabanis's early nineteenth-century publication, *Rapports du physique et du morale de l'homme* (Cabanis 1975) and also in Sechenov's *Reflexes of the brain* (Sechenov 1959; first published in 1863). Sechenov was a student of Claude Bernard and teacher of Pavlov. In the 1956 edition of Webster's New Collegiate Dictionary, behavior had already been identified as "The way in which an organism, organ or substance acts, especially in response to a stimulus" (Webster 1956). The concept was further articulated in a series of publications from conferences organized by Horace Magoun and Frank Fremont-Smith and edited by Mary A. B. Brazier (Brazier 1959; 1960; 1961; 1962; 1963). In the medical literature, cardiovascular responses were described as aspects of behavior at least as early as 1970 (Wolf 1970).

Engel's contribution has been to emphasize that visceral and circulatory behaviors do not occur as separate actions but are integrated into the total behavior of the organism. He points out that the integrative process depends upon interactive rather than hierarchical central control mechanisms. This view was proposed in 1963 by Brobeck and later cogently presented and documented in a FASEB symposium by its chairman, J. W. Manning and the other participants (Manning 1980). Engel's use of the term "conditional" to express the outcome of the neural interactions parallels Sherrington's (1946) way of explaining the behavior of autonomically innervated structures as "contingent."

Engel quotes Nadel et al. (1980, pp. 1495–6) to the effect that "when regulatory systems that share common effectors are presented with extreme conditions, the controlling and integrating mechanisms must search for the optimal compromise." A vivid illustration of such an optimal compromise is available in the work of Elsner and Gooden (1970), who demonstrated that the dive reflex in man elicited by face immersion caused a reduction of the reactive hyperaemia expected after release of an occluding pressure cuff on the arm. They showed a similar predominance of peripheral vasoconstriction during vigorous underwater swimming while the breath was held over what on land would have been wide vasodilatation in the exercising muscles (Elsner, Franklin, Van Citters & Kenney 1966).

Engel cites a 1976 publication by Blix as evidence that the elicitation of the dive reflex in ducks may be conditioned. Earlier demonstrations of the effects of emotionally significant circumstances on the dive reflex in alligators had been made by Anderson (1961), in seals, Scholander (1962), in ducks, Folkow (1966), and in humans by Wolf (1964; 1965). Engel's suggestion that the cardiovascular system can have a role in purposive behavior comparable to that of the somatomotor system is refreshing; and, indeed, since there are responses in anticipation (proactive in Engel's terms), it is difficult to escape the notion. Rushmer documented cardiovascular adjustments appropriate to exercise in dogs familiar with the treadmill procedure who were standing quietly alongside the apparatus prior to running (Rushmer & Smith 1959).

The useful phylogenetic perspective Engel provides emphasizes the growing repertoire of protective patterns that can be called upon in making adjustments to one's circumstances and the increasing complexity involved in making adaptive decisions. Engel's work has shown how patterned responses in monkeys can be manipulated by long term conditioning. His experiments are ingenious, elegantly designed, precisely focused, and convincing.

Engel points out the difficulties of attempting comparable studies in humans, especially noting the severe limitation on controls, but he neglects to highlight the limitations of studies with animals who cannot communicate their thoughts and emotions and in whom one can scarcely infer the sort of cognitive and emotional factors that enter so powerfully into the integrative process that determines visceral aspects of behavior in man.

Apart from urgent priorities of cardiovascular response when survival is at stake, as noted in apnea during submersion, what Engel calls contextual factors become dominant in determining what response pattern emerges. In man these factors consist of a complex of circumstances, timing, preconceptions, beliefs, social pressures, emotionally significant past experiences, self-doubts, aspirations, and personal values. These and other intangible but powerful forces, acting through the central neural circuitry, shape the response pattern and thereby provide a severe challenge to the investigator who would pose behavioral questions to man. As discouraging as the challenge may seem, however, there are strategies to meet it, strategies designed to yield not only quantifiable data but data on configuration, that is, the arrangement of circumstances in relation to pecularities of individuals (Schottstaedt et al. 1958).