Mark S. Blumberg
Greta Sokoloff
Department of Psychology
The University of Iowa
Iowa City, Iowa 52242

Thermoregulatory Competence and Behavioral Expression in the Young of Altricial Species—Revisited

Received 24 July 1997; accepted 27 October 1997

ABSTRACT: *The behavioral and physiological thermoregulatory capabilities of newborn and infant mammals have been studied for over half a century. Psychobiologists have noted that the infants of altricial species (e.g., rats) have physical and physiological limitations such that heat loss overwhelms heat production, thus forcing a reliance on behavioral thermoregulation for the maintenance of body temperature. Recent evidence, however, suggests that a modification of this view is justified. Specifically, throughout a range of moderately cold air temperatures, nonshivering thermogenesis by brown adipose tissue contributes significantly to the infant rat's behavioral and physiological adaptations to cold challenge. Given the prominent use of altricial species for the study of infant behavior, increased understanding of the infant's physiological responses to cold and the effect of thermal factors on behavior is warranted.* *© 1998 John Wiley & Sons, Inc.* Dev Psychobiol 33: 107–123, 1998

Keywords: *rat; hamster; thermoregulation; brown adipose tissue; homeostasis; development*

INTRODUCTION

Like oxygen and gravity, temperature is a basic feature of the environment that shapes and constrains biological activity. Temperature influences cellular metabolism (Schmidt-Nielsen, 1990) and muscular contraction (Bennett, 1984), it modulates many aspects of neuronal function from conduction velocity to refractory period (e.g., Swadlow, Waxman, & Weyand, 1981), and it even guides sexual differentiation in many reptiles (Deeming & Ferguson, 1989). The sensitivity of neural tissue to high temperatures has made necessary the evolution of elaborate mechanisms for protecting the brain from overheating, including the venous shunts of horned lizards (Heath, 1966) and the rete mirabile of many mammals (Baker, 1979). Threats of extreme cooling have led to the evolution of similarly inventive solutions, such as a brain heater tissue in swordfish (Carey, 1982) and "antifreeze" in the blood of coldwater fishes (DeVries, 1982).

Temperature is an especially important factor during development. During embryonic development, and regardless of whether we are considering a chick inside its egg or a human infant in utero, the thermal environment is maintained within narrow limits by the parent while the embryos are passive recipients of the heat supplied to them (Leon, 1986). With hatching or birth, however, young emerge from their thermally secure environments into a world where heat loss is a constant threat to survival. Suddenly, they must now

---

Correspondence to: M. S. Blumberg

Contract grant sponsor: NIMH
Contract grant number: MH 50701

CCC 0012-1630/98/020107-17

become active participants in the regulation of their body temperature.

The thermoregulatory capabilities of newborn and infant mammals have been the subject of experimental research for over 50 years. As we will see, our understanding and appreciation of those capabilities have been influenced profoundly by our expectations as to what constitutes "successful" thermoregulation. In part, our expectations arise from the idea that there exists a single core body temperature (e.g., rectal temperature) that (a) is representative of all relevant body temperatures and (b) will be maintained within a range of adultlike values if the infant is thermoregulating successfully. These expectations, however, have led us astray. Therefore, this article represents an attempt to reassess infant thermoregulation, especially that of altricial species such as the rat, based on recent physiological and behavioral data.

A BRIEF HISTORY

A common strategy in developmental studies of infant thermoregulation entails exposing pups to a very low air temperature and, by measuring rectal temperature, monitoring the "development of homeothermy" (e.g., Brody, 1943; Hahn, 1956). When tested in this way, developing rat pups are increasingly able to maintain rectal temperature in the cold from birth to 3 weeks of age. This general experimental approach to studying the development of homeothermy has been popular over the years, despite its considerable methodological and conceptual pitfalls.

In the experiment of Brody (1943), 1- to 22-day-old pups were placed in a container maintained at an air temperature of 15°C and rectal temperature was monitored. He concluded that thermoregulatory competence developed between the 2nd and 3rd week postpartum. Similarly, Hahn (1956) exposed young rats to an air temperature of 10°C and demonstrated the thermoregulatory importance of the development of fur and the control of piloerection. Based on Hahn's results, it was concluded that "physical thermoregulatory mechanisms develop between the 14th and 18th day" postpartum (p. 430). In both of these experiments, the particular choice of air temperature is not discussed, and one must wonder to what extent these choices influenced the conclusions of the experiments. For example, would Brody's 22-day-old pups have exhibited homeothermy had they been challenged at an air temperature of 0°C? And would the 1-day-old pups have exhibited homeothermy had they been challenged at an air temperature of only 30°C?

That earlier investigators did not ask these questions provides insight into the conceptual framework within which they were working. As was mentioned earlier, there has been a tendency to assess thermoregulatory capabilities based on the maintenance of a stable body temperature in the cold. But "cold" is a relative concept, and any investigation of a regulatory system requires the choice of appropriate experimental stimuli. This is exactly what Conklin and Heggeness (1971) understood when, in discussing their experiments, they wrote that they exposed their infant rats to air temperatures "that would evoke, but not overwhelm, regulatory functions" (p. 333). Therefore, testing infants at an extreme air temperature is not always an effective way to assess thermoregulatory capabilities—if the mechanisms are overwhelmed, then one cannot properly evaluate their control, efficacy, or development.

Taylor (1960) contributed to the development of a revised perspective by showing that newborn rats increase oxygen consumption significantly when exposed to an air temperature of 29°C. Taylor was unique in cautioning against superficial comparisons between the thermogenic capabilities of young rats of different ages—differences in size and insulation are intimately connected with age and cannot be ignored. In effect, Taylor argued against the relatively simplistic approach of assessing thermoregulatory competence by exposing pups to a single, arbitrary air temperature and measuring rectal temperature.

The determinants of heat loss in infants and adults were well known by the early 1960s: Surface-to-volume ratio, insulation, and vasomotor activity all contribute, passively or actively, to the promotion or retardation of heat loss. The mechanisms of heat gain, however, were somewhat more obscure at that time. Specifically, while the importance of shivering thermogenesis for adults was not in dispute, the ability of curarized animals to produce heat in the cold argued for a second form of heat production that was referred to as chemical or nonshivering thermogenesis (Hsieh, Carlson, & Gray, 1957). This form of thermogenesis was known to be stimulated by noradrenaline, but the site of action had not yet been identified. Then, in the early 1960s, Smith hypothesized that brown adipose tissue (BAT) is one source of nonshivering thermogenesis in adult mammals (Smith, 1964). The role of BAT as a thermogenic organ was quickly extended to apply to heat production in newborn rabbits and other mammalian species (e.g., Dawkins & Hull, 1964; Hull & Segall, 1965). By the end of the decade, the thermogenic function of BAT seemed irrefutable (Smith & Horwitz, 1969).

In reviewing the work of comparative physiologists following the discovery of the thermogenic function of BAT, Brück and Hinckel (1996) suggest that neonates can be divided into three categories. First, there are the precocial newborns (e.g., guinea pig, lamb, full-term human) that respond vigorously to cold challenge and are able to maintain body temperature at a stable level in the cold, albeit only within a narrow range of air temperatures. Second, there are the altricial newborns (e.g., rabbit, dog, rat) whose thermogenic responses, although present shortly after birth, are insufficient to retard heat loss so that their "body temperature drops on exposure to environmental temperatures slightly less than thermal neutrality" (Brück & Hinckel, 1996, p. 603). Finally, there are those animals (e.g., hamster, ground squirrel) that do not exhibit any thermogenic responses to cold for days or weeks after birth (Blumberg, 1997; Hissa, 1968).

When mammalian neonates are categorized in the way suggested by Brück and Hinckel, it appears that physiological mechanisms of thermoregulation are only effectively available to the precocial species. These animals, equipped with shivering and/or nonshivering thermogenesis as well as control over heat loss, resemble smaller and somewhat limited versions of their adult forms. Furthermore, according to this perspective, neonates in the other two categories cannot thermoregulate independently using physiological mechanisms alone; their limitations can only be overcome by using behavior, a subject to which we now turn.

THE IMPORTANCE OF BEHAVIOR

Because isolated newborn rats were thought to be physiologically incapable of successfully combating even moderate cold exposure, it became acceptable to refer to them as poikilotherms (e.g., Fowler & Kellogg, 1975; see Nedergaard, Connolly, & Cannon, 1986), primarily dependent on behavioral mechanisms for the maintenance of body temperature (Johanson, 1979; Kleitman & Satinoff, 1982). Poikilothermy has been defined as "large variability of body temperature as a function of ambient temperature in organisms without effective autonomic temperature regulation" (IUPS Thermal Commission, 1987, p. 577). Based on this definition, newborn rats, with their insufficient heat gain mechanisms and their uncontrollable heat loss, do indeed appear to exhibit the signs of poikilothermy.

The apparent poikilothermy of an isolated rat pup can be contrasted with the thermoregulatory competence of a huddle of rat pups. In a series of now-classic experiments, Alberts (1978) monitored the oxygen consumption and rectal temperature of pups allowed to huddle with littermates. He found that the huddle expands and contracts as air temperature increases and decreases, respectively, and that the heat conservation afforded by the favorable changes in surface-to-volume relations provides a significant metabolic savings to the individual pups. He concluded that "through individual competitive adjustments the huddle behaves as a self-regulating unit which provides warmth and insulation to all its members" (Alberts, 1978, p. 231).

The elegance and power of Alberts' (1978) analyses crystallized for psychobiologists the significance of behavior for infants facing the problem of rapid heat loss. This research has been so influential among psychobiologists that the neonate's physiological means of heat production has faded in importance. For example, Satinoff (1996), who has been instrumental in promoting the importance of behavioral mechanisms for thermoregulation, has written that "although infant rodents can increase their metabolic rate from birth, this capability is nearly useless because they cannot conserve heat and have practically no insulation" (p. 494). This view, that endogenous heat production by infant rodents is ineffectual, is widely accepted, as evidenced by its adoption (in one form or another) into popular textbooks in physiological psychology. For example, Rosenzweig, Leiman, and Breedlove (1996) write that "newborn rats are not capable of endothermic regulation" (p. 460) and Carlson (1994) writes that newborn rats and mice "are poikilothermous [sic] ("cold-blooded"); their brain is not yet developed enough to regulate body temperature" (p. 324).

Despite a long history, the study of thermoregulation in individual infants has never properly addressed the function or regulatory control of BAT thermogenesis at moderate air temperatures. Moreover, the development of thermoregulation has been viewed too narrowly as a process aimed toward adult capabilities rather than a process in which pups have evolved solutions that are unique to their physiological needs during development. Therefore, what is needed is an approach that addresses the regulatory principles that govern infant thermogenesis and the consequences of that thermogenesis for the pup's physiological and behavioral development. Such an approach, and the empirical data that support it, will be detailed later in this article. Next, we review recent research in a variety of species that provides an alternative perspective for assessing the thermoregulatory capabilities of infant rats.

COMPARTMENTALIZATION IN THERMOREGULATORY SYSTEMS FROM INSECTS TO MAMMALS

Over the past three decades, evidence has accrued that suggests a general theme: Some thermoregulatory systems have evolved to protect particular organ systems from excessive heating or cooling. Therefore, perhaps more often than not, one finds animals with substantial heterogeneity in the distribution of temperatures throughout the body core. A brief review of this literature follows.

Insects

Until recently, these small, primitive creatures were considered classic illustrations of poikilothermy, a designation that once impeded the study of insect thermoregulation. As Heinrich (1993) points out, such designations can get in the way of productive science:

> From a limited perspective it would be possible to classify different insects in any of a variety of terms—as poikilotherms, cold-blooded, warm-blooded, heterotherms, endotherms, heliotherms, and even homeotherms. Terms tend to categorize, however, and categorization is not helpful in understanding thermal mechanisms in insects because many assumptions are associated with the terms. (p. 9)

Placing such assumptions aside has led to the discovery of a number of interesting behavioral and physiological mechanisms by which insects solve their thermal problems. For example, moths exhibit a preflight shivering response that raises muscle temperature to a level adequate to sustain flight (Heinrich, 1987). Because these flight muscles are located in the thorax, thoracic temperature in flying moths is higher than abdominal temperature. In fact, across a range of air temperatures from 0–25°C, the difference between thoracic and abdominal temperatures ranges from 25–10°C, respectively, an enormous thermal gradient within an animal that weighs only 2–3 g and therefore has a large surface-to-volume ratio.

Fish

Like insects, fish have been considered prototypical ectotherms, their body temperatures increasing and decreasing with the temperature of the surrounding water. There are a number of fish species, however, that do not fit with this traditional view. For example, bluefin tuna regulate the temperatures of muscle, eye, and brain by conserving metabolic heat using a countercurrent heat exchange system (Linthicum & Carey, 1972). Swordfish, billfishes, and some sharks have added to this vascular heat exchange system a mass of thermogenic tissue, derived from muscle, that selectively warms the eye and brain (Block, 1986; Block & Carey, 1985; Carey, 1982). Therefore, it appears that large pelagic predators that rely heavily on visual tracking of prey have evolved thermoregulatory systems that help to buffer their nervous systems against the thermal fluctuations normally encountered in their daily movements.

Selective Brain Cooling in Reptiles, Birds, and Mammals

Because the brain is more easily damaged by high temperatures than other bodily organs (Heikkila & Brown, 1979; Millan, Murdock, Bleier, & Siegel, 1979), a number of species have evolved physiological mechanisms that selectively cool the brain during exercise and during exposure to high air temperatures. For example, Crawford (1972) studied a lizard species *(Sauromalus obesus)* that, when panting, can maintain brain temperature nearly 3°C below an air temperature of 45°C.

In birds and mammals, complex vascular arrangements combine with evaporative cooling mechanisms to yield impressive abilities to protect the brain from overheating (Baker, 1979; Kilgore, Bernstein, & Hudson, 1976). For example, gazelles can maintain brain temperature as much as 3°C below body temperature during an extended run—blood is cooled evaporatively in the nasal passages that, in turn, cools arterial blood flowing to the brain (Taylor & Lyman, 1972).

Flying birds maintain body temperature at a higher level than nonflying birds and mammals (Caputa, 1984). A high body temperature may be an adaptation for continual readiness for flight, but this readiness comes with the constant risk of hyperthermia. Therefore, birds have evolved an array of body and brain cooling mechanisms, including panting, gular flutter, and an esophageal heat exchanger (Dawson, 1982; Gaunt, 1980). It has also been shown in pigeons that cooling of blood flowing through the cornea enhances selective brain cooling during flight (Pinshow, Bernstein, Lopez, & Kleinhaus, 1982).

All of the above examples illustrate how thermoregulatory systems have evolved to warm or cool bodily compartments, from the muscle-rich thorax of moths to the heat-sensitive brain tissue of mammals. When we recognize the functional significance of these particular compartments, we are led to ask experimental questions that otherwise would have been overlooked. Moreover, these examples show us that there are many body temperatures, not just one, and the experimenter's choice of where to measure body temperature (e.g., rectum, brain, heart, eye, skin) can have important theoretical implications. Therefore, using the above examples as guideposts, we now turn to the question of the functional significance of BAT thermogenesis in infant rats.

THE PHYSIOLOGICAL AND BEHAVIORAL SIGNIFICANCE OF BAT THERMOGENESIS

In order to advance our understanding of thermoregulation in altricial neonates, the following questions must be addressed: (a) What are the appropriate measures of body temperature? (b) Is BAT thermogenesis regulated? (c) Does BAT thermogenesis contribute significantly to the infant's behavioral and physiological adaptation to cold challenge, even in isolated individuals? These questions are very closely related, as the following discussion will demonstrate.

Choosing an appropriate measure of body temperature, like any experimental measure, reflects a balance between theory and method. As we have seen, the search by early investigators for the age at which infants attain homeothermy required a measure that had meaning from infancy to adulthood. Skin temperature would not be appropriate because of the substantial changes in size and insulation during development. Maintenance of deep body temperature, on the other hand, has been considered the primary goal of the thermoregulatory system, and no measure of core body temperature is as easily attained as rectal temperature. Therefore, with respect to the appropriate measure of body temperature, theory and method apparently complement one another.

The discovery that nonshivering thermogenesis is attributable to BAT has had little impact on the assumption that rectal temperature is the valid measure of thermoregulatory success. But even the earliest articles detailing the vascular arrangement of BAT provided well-reasoned arguments for questioning this assumption. For example, Smith and Roberts (1964) wrote:

> Considered a priori, the absolutely small amount of heat produced by brown fat tissue could be of no intrinsic significance relative to total body heat production unless this heat were in some way brought to bear upon a relatively isolated heat sink of small size and perhaps of high sensitivity to temperature. Of organs vital to survival in cold, the thoracic and cervical regions of the body might be satisfied by direct conductance or vascular connection of heat from such generative loci. . . . [T]he finding by Sulzer in 1774 . . . of a direct venous connection between interscapular brown fat and the azygous vein could be readily adduced as indicative of a direct convective heat transfer to the heart. (p. 146)

While these investigators were addressing BAT thermogenesis in adults, the argument can also be applied to infant animals. Would it not make sense for an infant rat, facing profound problems of heat loss, to direct and isolate its limited heat production to those parts of the body, such as the cervical and thoracic spinal cord and the heart and lungs, that would most seriously affect survival in the cold? In addition, is it not interesting that two of the largest BAT depots, that is, the interscapular and cervical BAT pads (Smith, 1964), are ideally suited for the delivery of heat either directly (i.e., conductively) or indirectly (i.e., convectively via the blood) to those vital structures?

Although this argument may seem reasonable, it nonetheless contradicts the common assumption that BAT thermogenesis provides warmth to the body as a whole and its efficacy can be measured as a high and stable rectal temperature. In contrast, Smith and Roberts (1964) seem to argue that heat produced by BAT is compartmentalized or, at least, is directed primarily toward certain vital structures. This basic idea provided a foundation for the experiments that will now be described.

In a series of studies of 2-day-old and week-old rats, we have monitored BAT thermogenesis over a well-defined range of air temperatures and, building on this information, have assessed a series of physiological and behavioral variables (see Table 1 for a summary of the experiments described below). The physiological variables represent systems that influence or are influenced by BAT thermogenesis during cold exposure — for example, the respiratory and cardiovascular systems. The behavioral variables include a measure of active sleep (i.e., myoclonic twitching of the distal limbs and tail; Gramsbergen, Schwartze, & Prechtl, 1970) and a vocalization that is emitted at the ultrasonic frequency of 40 kHz. Altogether, these studies begin to provide a coherent picture of the organization of and the interactions between physiological and behavioral responding in the infants of this altricial species.

Figure 1 is an illustration adapted from an infrared thermograph of the dorsal surface of a week-old rat pup in a cold environment. The innermost circle in the interscapular area, which overlies a large depot of BAT, indicates the region of highest skin temperature, and it is surrounded by concentric regions of lower skin temperatures. In this figure, the thermal gradient from the interscapular region to the lower back is greater than 2°C. Therefore, using conventional methods of temperature measurement, BAT thermogenesis can be estimated using thermocouples placed on the skin in the interscapular region and at a site distant from the BAT pad, such as in the lower back (i.e., lumbar region; Blumberg & Stolba, 1996). Because BAT thermogenesis is an aerobic process, simultaneous measurement of oxygen consumption provides confirmatory evidence that BAT is producing heat (Heim & Hull, 1966).

Table 1. Physiological and Behavioral Responses in Unmanipulated Week-Old Rats. The Table Should be Read as if a Pup Were Being Cooled Successively From a Thermoneutral to a Moderate Air Temperature, and Then to an Extreme Air Temperature. The Air Temperatures Indicated are Approximate and Vary Depending on Age, Strain, Litter Size, Body Weight, and Other Factors

	Thermoneutral Air Temperatures (35–36°C)	Moderate Air Temperatures (25–34°C)	Extreme Air Temperatures (<25°C)	References
Interscapular Temperature	High, Stable?	High, Relatively Stable	Low, Relatively Unstable	Blumberg & Stolba, 1996; Blumberg & Sokoloff, 1997
BAT Heat Production	No	Progressive Increase	Depression	Blumberg & Stolba, 1996
Oxygen Consumption	Low	Progressive Increase	Depression	Blumberg & Stolba, 1996
Respiratory Rate	Low	Progressive Increase	Depression	Sokoloff & Blumberg, 1997
Cardiac Rate	Normal	Normal	Depression	Blumberg, Sokoloff, & Kirby, 1997
Blood Pressure	Normal	Normal	Normal	Kirby & Blumberg, 1998
Rate of Myoclonic Twitching	High	High	Depression	Blumberg & Stolba, 1996; Sokoloff & Blumberg, 1998
Ultrasound Production	No	No	Yes	Blumberg & Stolba, 1996; Sokoloff & Blumberg, 1997

Air temperature, of course, is a primary controlling parameter of BAT thermogenesis, so it is important to begin by defining the ranges of air temperatures at which BAT thermogenesis is initiated, increases progressively, and is overwhelmed. To define those ranges, we measured interscapular temperature, back temperature, and oxygen consumption in pups acclimated to a thermoneutral air temperature of 35°C and then exposed them to a series of cold challenges. In these experiments, we have focused primarily on 1-week-olds (6–8 days of age), although we have performed many of the same experiments on 2-day-olds.

In week-old rats, we have distinguished three ranges of air temperatures based on the thermogenic responses that they elicit. First, at air temperatures of 35–36°C, pups do not exhibit BAT thermogenesis; these warm air temperatures can be referred to as lying within a thermoneutral zone or a zone of least thermoregulatory effort (Satinoff, 1996). Second, as air temperature is decreased, a threshold is reached below which BAT thermogenesis is stimulated; for week-old rats, this lower critical temperature is approximately 34°C (Spiers & Adair, 1986). As air temperature is decreased progressively, BAT thermogenesis increases progressively. Finally, an air temperature is reached where BAT thermogenesis increases no further; for week-old rats, this air temperature of maximal BAT thermogenesis is approximately 25°C (Sokoloff & Blumberg, 1997; Spiers & Adair, 1986). For the remainder of this article, air temperatures ranging from 34°C to 25°C will be referred to as moderate while air temperatures below 25°C will be referred to as extreme. (It should be stressed that these particular air temperature "zones" are specific to isolated week-old rats and that these values differ for pups at other ages; in other words, the thermoregulatory challenges used must be scaled to an infant's age, size, and insulation.)

Graphical representations of the physiological correlates of moderate and extreme thermal challenge are presented in Figure 2. Each plot is a state space diagram for individual pups in which oxygen consumption is plotted against interscapular temperature. Although the passage of time is not depicted in these plots, they do provide an enhanced sense of the regulation of BAT thermogenesis during cold exposure.

The test begins with a pup acclimated in a metabolic chamber in which air temperature is maintained at 35°C. After 45 min of acclimation, the pup exhibits an interscapular temperature of 38°C and a low value of oxygen consumption. Air temperature is then decreased rapidly to 30°C (Figure 2a), and the pup responds initially with a decrease in interscapular tem-

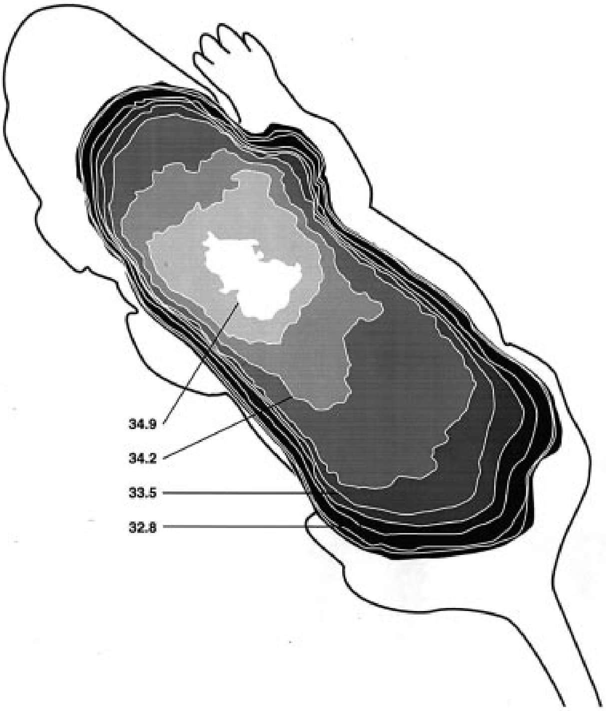

FIGURE 1 Illustration adapted from an infrared thermograph of the dorsal skin surface of a week-old rat in the cold. The bright spot overlying the interscapular region represents the area of highest skin temperature, and it reflects thermogenesis by the interscapular brown fat pad located just beneath the skin surface. Note the pronounced thermal gradient from the interscapular area to the lower back. The numbers to the side of the illustration represent approximate skin temperatures in degrees Celsius.

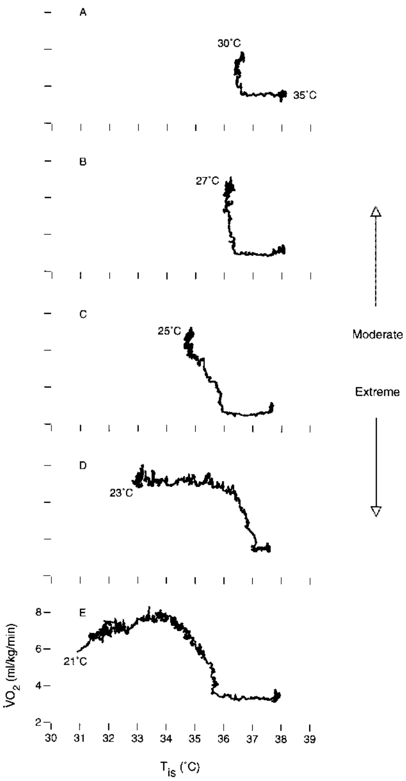

FIGURE 2 State–space diagrams for individual week-old rats in which oxygen consumption (VO_2) is plotted against interscapular temperature (T_{is}). Air temperature at the beginning of each test was 35°C. Temperatures at the left of each plot indicate the final air temperature for that test. (adapted from Sokoloff & Blumberg, 1997).

perature and an unchanged rate of oxygen consumption. At some point, however, a change occurs: Interscapular temperature stops falling and oxygen consumption begins to increase as a result of increased BAT thermogenesis. Within the state space, the trajectory rises vertically until it reaches a new settling point. When a pup experiences a decrease in air temperature to 27°C rather than 30°C, it exhibits a similar response (Figure 2b).

As stated above, the transition from moderate to extreme cooling is defined as the point at which BAT thermogenesis is maximized. When this occurs, interscapular temperature should exhibit greater dependence on air temperature, and this is exactly what is observed. Specifically, when air temperature is decreased to 25°C (Figure 2c), the trajectory is skewed to lower interscapular temperatures. A pup exposed to an extreme air temperature of 23°C (Figure 2d) shows an even greater decrease in interscapular temperature, although oxygen consumption maintains a high value. Finally, an extreme thermal challenge of 21°C (Figure 2e) results not only in a decrease in interscapular temperature but a depression of oxygen consumption as well.

Having clear and operationalized definitions of moderate and extreme thermal challenge is useful because it allows us to begin delving deeper into the physiological correlates of these challenges and their behavioral consequences. One immediate conceptual difficulty that is raised by the patterns of responses in Figure 2 relates to the question of thermal comfort. Specifically, given that rectal temperature in week-old rats decreases even during moderate thermal challenges (Conklin & Heggeness, 1971; Spiers & Adair, 1986; Takano, Mohri, & Nagasaka, 1979), do these pups exhibit physiological or behavioral signs of stress?

To aid in answering this question and as a thought experiment, consider the following scenario based on a traditional control systems approach to thermoregulation (Houk, 1988). Let's assume that it is only at a thermoneutral air temperature that a pup is able to maintain core body temperature at the desired "set-point" level. It follows from this assumption that a pup exposed to a subthermoneutral air temperature would detect a discrepancy between set-point temperature and falling body temperature and would in turn activate BAT thermogenesis. However, as many have found, BAT thermogenesis is not capable of compensating for heat loss and thus core body temperature decreases (Conklin & Heggeness, 1971; Spiers & Adair, 1986; Takano, et al., 1979). Therefore, to counter this situation, the pup would either have to (a) recruit other behavioral and/or physiological mechanisms to raise core body temperature back to the set-point level or (b) decrease set-point to erase the discrepancy with body temperature (see Mrosovsky, 1990).

For the remainder of this section, we will assess the plausibility of the above scenario by citing the available experimental evidence. It will be shown that neither the physiological nor the behavioral data support the commonly held view that isolated pups are overwhelmed by the thermal challenges posed by all subthermoneutral air temperatures (see Brück & Hinckel, 1996). Specifically, we will see that isolated pups adapt successfully to moderate thermal challenge and that they do so primarily through BAT activation.

As shown in Figure 2, pups arrive at settling points regardless of whether they are exposed to moderate or extreme air temperatures. To determine whether these settling points differ with respect to (a) the ability of pups to defend them and (b) the speed and accuracy with which they are defended (measures of relative stability; Kelso, 1995), perturbation experiments were performed (Blumberg & Sokoloff, 1997). Pups were cooled either to a moderate air temperature (30.5°C) or to an extreme air temperature (23°C). After they had settled at one of these two air temperatures, pups were exposed to a 3.7°C air temperature perturbation in the positive or negative direction. Overall, we found that the pups in the moderate condition were better able to defend interscapular temperature against the perturbation than were the pups in the extreme condition, and they did so by increasing or decreasing BAT thermogenesis. It was concluded from these data that the settling points at a moderate air temperature are relatively stable in comparison to settling points at an extreme air temperature.

Perhaps the most striking result of the perturbation experiment was the physiological response of the moderately challenged pups to a positive air temperature perturbation (Figure 3). As air temperature increased during the positive perturbation, these pups exhibited rapid *decreases* in heat production that prevented interscapular temperature from increasing. Figure 3 shows that this response was the mirror image of the response to a negative air temperature perturbation. In other words, the system was behaving like a prototypical homeostatic system. Surprisingly, the system is behaving homeostatically at a subthermoneutral air temperature (i.e., 30°C). Recall our thought experiment: If, during moderate cold exposure, the pups' body temperatures are indeed below the thermoneutral set-point level, then one would expect these pups to continue BAT heat production during the positive air temperature perturbation so that body temperature could increase as quickly as possible. That the pups quickly *decreased* BAT thermogenesis during the positive perturbation suggests that this was not the case.

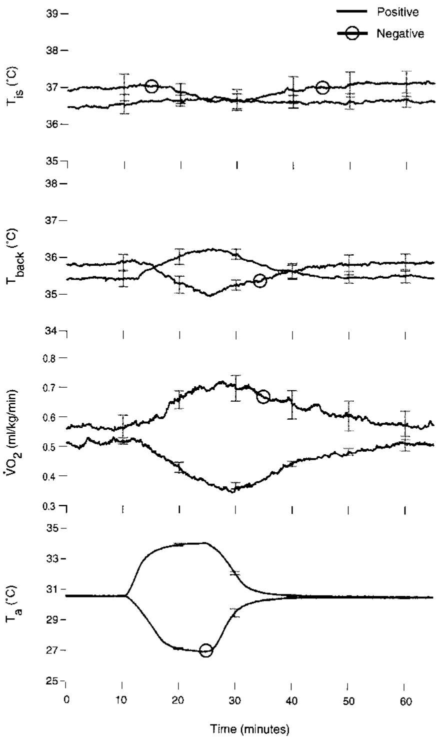

FIGURE 3 Mean values of interscapular temperature (T_{is}), back temperature (T_{back}), oxygen consumption (VO_2), and air temperature (T_a) for moderately cooled 7- to 8-day-old rats experiencing either positive (*n* = 4) or negative (*n* = 4) air temperature perturbations. The oxygen consumption responses to the two air temperature perturbations are mirror images of one another, and changes in T_{is} are dampened in relation to changes in T_{back}. Therefore, pups exhibit homeostatic thermoregulatory responses even at a subthermoneutral air temperature. (adapted from Blumberg & Sokoloff, 1997).

Behavioral responses can also contribute to our assessment of the differential effects of moderate and extreme cooling. Because infant rats, like most mammals, spend the majority of their time in active sleep, we have monitored active sleep during moderate and extreme thermal challenges (Blumberg & Stolba, 1996; Sokoloff & Blumberg, 1998). In infant rats, a predominant indicator of active sleep is myoclonic twitching of the distal limbs and tail, a behavior that is easily and reliably scored by a trained observer (Blumberg & Lucas, 1996; Gramsbergen et al., 1970; Jouvet-Mounier, Astic, & Lacote, 1970).

In one experiment, week-old rats were acclimated to a metabolic chamber at a thermoneutral air temperature (35.5°C), followed by a fast drop in air temperature to either a moderate (30°C) or extreme (21°C) level (Blumberg & Stolba, 1996). The test lasted 70 min (a 10-min baseline period at 35.5°C plus a 60-min period of cooling), during which the observer scored the incidence of myoclonic twitching. The results indicated that although extreme cooling significantly reduced myoclonic twitching over the course of the test, moderate cooling elicited no change in twitching. Moreover, as already described, pups in the moderate condition were better able to maintain and stabilize interscapular temperature than were pups in the extreme condition. Finally, a parallel experiment in 2-day-olds using age-appropriate air temperatures yielded similar results (Blumberg & Stolba, 1996).

In addition to myoclonic twitching, we have also analyzed the vocal responses of rat pups to cold. Following up on earlier work showing that cold is a primary stimulus for eliciting ultrasound production by rat pups (Okon, 1971), it was noted that pups start to vocalize during cold exposure at the same time that they initiate BAT thermogenesis (Blumberg & Alberts, 1990). The conclusion that a relation exists between initiation of BAT thermogenesis and ultrasound production was modified by a subsequent experiment in which it was found that pups only vocalize during extreme cold exposure, even though BAT thermogenesis is initiated during moderate cold exposure (Blumberg & Stolba, 1996). More detailed experimental manipulations of air temperature supported this finding (Sokoloff & Blumberg, 1997). Therefore, whether this vocalization is interpreted as a communicatory act designed to elicit maternal retrieval to the nest (e.g., Hofer & Shair, 1978) or as an acoustic by-product of respiratory (Blumberg & Alberts, 1990) and/or cardiovascular (Kirby & Blumberg, 1998) maneuvers, the incidence of ultrasound production during extreme cooling, but not during moderate cooling, points out yet another qualitative difference between these two ranges of air temperature.

We began this section with three fundamental questions about infant thermoregulation. First, we have shown how interscapular temperature, when combined with other thermal and metabolic measures, is more informative for assessing a pup's physiological state than is rectal temperature alone. Second, we have provided evidence that BAT thermogenesis, even in isolated pups, is regulated during moderate cold exposure. Finally, we have shown how BAT thermogenesis contributes to the pup's behavioral adaptation to cold. We have not yet discussed, however, how the heat produced by BAT contributes to the pup's physiological adaptation to cold.

To address this issue, we go back to the first articles describing BAT as the source of nonshivering thermogenesis. Recall that Smith and Roberts (1964), in noting the venous outflow from BAT, suggested that the "direct venous connection between interscapular brown fat and the azygous vein could be readily adduced as indicative of a direct convective heat transfer to the heart" (p. 146). This observation, in conjunction with earlier studies demonstrating the profound effects of cooling on heart rate (e.g., Fairfield, 1948; Lyman & Blinks, 1959), suggested a possible role for BAT thermogenesis in the maintenance of cardiac function during cold challenge in infants.

To assess the contribution of BAT thermogenesis to cardiac rate regulation, the electrocardiogram of week-old rats was monitored as pups were exposed to a series of moderate and extreme air temperatures (Blumberg, Sokoloff, & Kirby, 1997). It was found that at air temperatures where interscapular temperature was maintained, cardiac rate was also maintained (Figure 4). At the extreme air temperature of 17°C, however, when interscapular temperature fell, cardiac rate fell significantly. In a separate experiment, when pups were administered chlorisondamine, a ganglionic blocker that prevents neural control of the heart as well as BAT, heart rate fell in lock-step with interscapular temperature. (Again, a parallel experiment with 2-day-olds yielded similar results.) Finally, experiments employing pharmacological activation of BAT and manipulation of interscapular temperature have provided further support for the hypothesis that BAT thermogenesis contributes significantly to the regulation of cardiac rate during cold challenge (Sokoloff, Kirby, & Blumberg, in press).

Cardiac rate is just one of two variables that determine cardiac output (i.e., the amount of blood pumped by the heart per unit time). The second component of cardiac output is stroke volume, that is, the volume of blood forced out during each individual contraction. In those infant mammals studied thus far, cardiac output is primarily determined by cardiac rate due to limitations in the infant's ability to modulate stroke volume (e.g., Teitel et al., 1985). Therefore, the falling heart rate of infant rats during extreme cooling suggests that cardiac output is falling as well, which

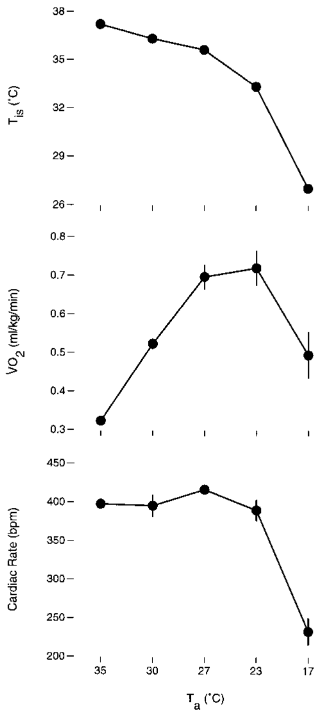

FIGURE 4 Mean values of interscapular temperature (T_{is}), oxygen consumption (VO_2), and cardiac rate (beats per minute, bpm) for 7- to 8-day-old rats at various air temperatures (T_a). Cardiac rate decreases significantly only when the limits of BAT thermogenesis are surpassed and T_{is} decreases. (adapted from Blumberg, Sokoloff, & Kirby, 1997).

would in turn suggest that such pups are facing related hemodynamic difficulties such as decreased arterial blood pressure. But, when blood pressure was monitored from the descending abdominal aorta in week-old pups during moderate and extreme cooling, no such decreases in blood pressure were detected (Kirby & Blumberg, 1998). As Table 1 shows, blood pressure is the one variable measured thus far that does not exhibit a change across the transition from moderate to extreme cold exposure. The mechanisms by which pups maintain blood pressure during extreme cooling have not yet been determined, but it is likely that one such mechanism is peripheral vasoconstriction.

The results presented in Table 1 tell a consistent story regarding the physiological and behavioral adaptations of week-old rats during cold exposure. During moderate cold exposure, pups increase BAT thermogenesis and, by doing so, regulate interscapular temperature or a correlate. The increase in oxygen utilization of BAT is supported by an increase in respiratory rate (Sokoloff & Blumberg, 1997). The heat produced by BAT contributes directly to the maintenance of cardiac rate, and may also help protect myoclonic twitching and inhibit ultrasound production. Therefore, from a physiological and behavioral standpoint, moderately cooled pups do not appear to be thermally stressed.

Recalling the thought experiment described earlier, it is possible that pups decrease set-point during moderate cooling to remove the discrepancy between body temperature and set-point temperature. This would be an example of rheostasis, or set-point modulation (Mrosovsky, 1990). Unfortunately, this notion of set-point modulation is very difficult to test experimentally. Perhaps it is preferable to simply suggest that the thermoregulatory responses of isolated pups during moderate, but not extreme, cooling are regulated and contribute significantly to the physiological and behavioral adaptations of rat pups to cold.

COMPARATIVE ASPECTS OF BEHAVIORAL AND PHYSIOLOGICAL THERMOREGULATION

In light of the findings summarized in Table 1, it now seems unwarranted to dismiss as inconsequential the thermoregulatory mechanisms used by rat pups isolated in the cold. Next, we assess the value of BAT thermogenesis, and test the generalizability of our functional hypotheses, by examining the behavioral and physiological responses of infant Syrian golden hamsters *(Mesocricetus auratus)* to various levels of cold challenge. Hamsters provide an interesting comparison group to rats because they do not exhibit endogenous heat production during the first 2 weeks after birth (Hissa, 1968).

Although hamsters have been referred to as “immature” by some investigators (e.g., Nedergaard et al., 1986), they simply do not fit easily along the conventional altricial/precocial continuum. With a gestation of only 16 days, golden hamsters are relatively precocial with respect to locomotor abilities, independent feeding, fur growth, and eye opening, but relatively altricial with respect to physiological mechanisms of thermoregulation (Daly, 1976; Schoenfeld & Leonard, 1985). Specifically, golden hamsters exhibit neither shivering nor nonshivering thermogenesis until approximately 2 weeks postpartum (Blumberg, 1997; Hissa, 1968). With respect to behavioral thermoregulation, however, newborn hamsters far outstrip newborn rats in their ability to rapidly move toward warmth (rats: Johanson, 1979; Kleitman & Satinoff, 1982; hamsters: Leonard, 1974, 1982). Therefore, there appears to be a trade-off between behavioral and physiological mechanisms of thermoregulation in these two species. Whether this is a true trade-off in that heightened development of one system requires inhibition of the other is an open question at this time.

Given the findings, described earlier, relating BAT thermogenesis and cardiac rate in infant rats, the question was raised as to whether hamsters can only maintain cardiac rate in the cold when thermogenic mechanisms have matured. When this hypothesis was tested, it was found that cardiac rate fell in lock-step with interscapular temperature even during mild cooling in hamster pups 12 days of age and younger (Blumberg, 1997). In contrast, by 13 days of age when pups began exhibiting BAT thermogenesis, interscapular temperature and cardiac rate were maintained. Therefore, as in infant rats, young hamsters exhibit a strong relation between endogenous heat production and cardiac rate regulation.

From the above experiments, it became apparent that the physiological responses of hamsters less than 10 days of age bear a striking resemblance to those of week-old rats that have been ganglionically blocked. Noting this resemblance, we revisited the question of whether BAT thermogenesis protects sleep-related behaviors during cold exposure by monitoring the myoclonic twitching of week-old untreated rats, ganglionically blocked rats, and untreated hamsters (Figure 5; Sokoloff & Blumberg, 1998). Just as with cardiac rate, and as expected from our previous study (Blumberg & Stolba, 1996), the untreated rat pups exhibited high levels of twitching at moderate air temperatures and low levels at extreme air temperatures. In contrast, twitching in both the ganglionically blocked rats and the untreated hamsters decreased in lock-step with air temperature. Further experiments in infant rats in which BAT thermogenesis was selectively activated using a β_3 agonist and in which the temperature of the interscapular region was manipulated using a thermode provide additional support to the hypothesis that BAT thermogenesis protects myoclonic twitching in cold-exposed infants (Sokoloff & Blumberg, 1998). Whether these thermal effects on twitching are mediated directly by temperature-sensitive neural elements (for example, in the cervical spinal cord; cf. Brück & Wünnenberg, 1970) or indirectly through other systems (e.g., the cardiovascular system) remains for further study.

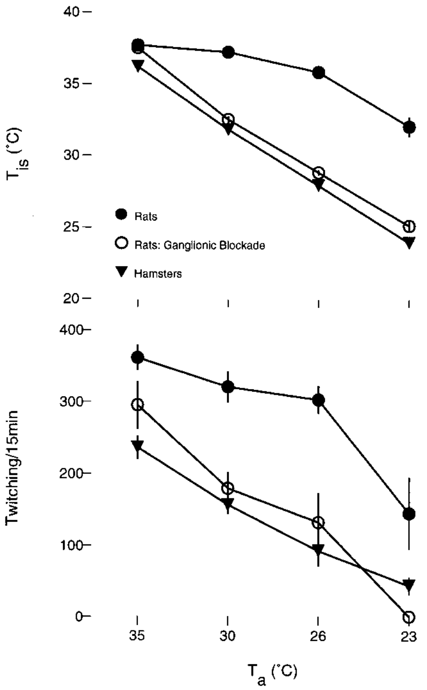

FIGURE 5 Mean values of interscapular temperature (T_{is}) and number of 1-s time bins in which myoclonic twitching was detected during a 15-min observation period for 6- to 8-day-old rats (circles) and Syrian golden hamsters (filled triangles) at various air temperatures (T_a). Rat pups were either untreated (filled circles) or pretreated with a ganglionic blocker (unfilled circles). Untreated rat pups increased BAT thermogenesis during moderate cooling, resulting in the maintenance of T_{is} and high rates of myoclonic twitching. However, during extreme cooling, both T_{is} and myoclonic twitching decreased substantially. In contrast, ganglionic blockade inhibited BAT thermogenesis at all subthermoneutral T_as and T_{is} and myoclonic twitching decreased progressively. Hamster pups do not exhibit endogenous heat production at this age and exhibited responses that were similar to the ganstionically blocked rats. (adapted from Sokoloff & Blumberg, 1998).

THERMAL CONSIDERATIONS IN THE STUDY OF INFANT BEHAVIOR

Although the thermoregulatory capabilities of infant rats are of interest to a relatively small group of researchers, the details of those capabilities should be of concern to all developmental psychobiologists, especially those working with infant rats and other altricial species. This is because temperature is both one of the primary environmental concerns of developing mammals and an influential modulator of behavior (Leon, 1986; Satinoff, 1991). As discussed previously, infant rats maintained at a thermoneutral or moderate air temperature exhibit high rates of myoclonic twitching and are only significantly aroused at extreme air temperatures (Blumberg & Stolba, 1996; Sokoloff & Blumberg, 1998). This simple fact makes it all the more important that researchers be aware of the role that the thermal environment plays in modulating infant behaviors.

Table 2 presents age and air temperature informa-

Table 2. A Selected List of Psychobiological Studies of Isolated Infant Rats Across a Range of Behavioral Paradigms. Studies by the Present Authors are Not Included. In Some Cases, Room Temperature is Not Explicitly Stated in the Article But Could Be Inferred From Other Information; Normally, Room Temperature is Approximately 22°C

Behavior	Age (days)	Air Temperature	References
Learning:			
Operant	1	33°C	Johanson & Hall, 1979
	3	30°C	Moran et al., 1981
Classical	0–4	30°C	Bachevalier & Blozovski, 1980
	3–6	35°C	Martin & Alberts, 1982
	4,8	Room	Miller et al., 1990
Habituation	6,12,18	32°C	Swithers-Mulvey et al., 1991
Ultrasound Production	1–28	Room	Noirot, 1968
	0–19	10°C	Naito & Tonoue, 1987
	9–10	25°C	Goodwin et al., 1994
	3,10,18	22°C, 30°C†	Carden et al., 1994
Motor Behaviors	3–10	Room	Bignall, 1974
	1–21	21–24.5°C	Altman & Sudarshan, 1975
	0–21	Room	Weber & Stelzner, 1977
Sleep Behaviors	0–17	Not clear	Jouvet-Mounier et al., 1969
	2–30	26–33°C‡	Gramsbergen et al., 1970
	1–17	Room	LaPointe & Nosal, 1979
	10–25	27–30°C	Van Someren et al., 1990

†Colder air temperature used for youngest age. ‡Air temperature adjusted appropriately to the animal's age.

tion for a representative selection of behavioral studies of infant rats. The studies presented entail a variety of behavioral paradigms, from learning to motor behavior, and none of these studies is concerned directly with the thermal modulation of behavior. It is apparent that some studies test pups of a single age while others examine developmental changes across ages. But what is perhaps most striking is the wide range of air temperatures, from thermoneutral to extreme, used to study these various behaviors. Moreover, this single dimension of air temperature does not fully capture the ways in which thermal factors differ between psychobiological studies. For example, in some studies pups are tested after a period of acclimation to a specific air temperature, while in others pups are tested immediately upon transfer from the nest.

The air temperatures used in various behavioral paradigms do not appear to be random (Table 2). For example, most learning studies involve the testing of pups at air temperatures above 30°C, while studies of motor behavior are typically done at room temperature. In this regard, consider Altman and Sudarshan's (1975) examination of the development of motor behaviors in rats. Pups, aged 1–21 days, were given a battery of tests that assessed a number of behaviors including walking, righting, rearing, and climbing. These investigators did not control the environmental conditions of their experiments, and they acknowledge that this lack of control was a "probable source of variability" in their results (p. 897). In all of their tests, pups were tested at room temperature which would constitute an extreme thermal challenge for the pups less than one week of age but would gradually become only a moderate challenge for older pups. Before testing, the pups were removed from the home cage and "carried to the testing laboratory, identified individually with a felt-tip marker, and weighed" (p. 896). Because infants cool very quickly at room temperature (Blumberg, Efimova, & Alberts, 1992b), it is highly likely that the body temperatures of the different-aged subjects in Altman and Sudarshan's experiments were very different when the pups were tested, and thus it is possible that some of Altman and Sudarshan's developmental findings were influenced by interactions between behavior, body temperature, and physiological activation.

As shown in Table 2, many investigators of learning in infants test their subjects in air temperatures of 30–35°C. For example, Hall and his colleagues, in their investigations of ingestive behaviors, typically test their newborn and infant rats in an incubator at an air temperature of approximately 32°C (e.g., Johanson & Hall, 1979; Swithers-Mulvey, Miller, & Hall, 1991). The choice of this air temperature for testing derives in part from findings demonstrating that the behaviors of food-deprived pups in response to food (e.g., milk intake, activity, mouthing, probing) are more prevalent at warmer air temperatures (Johanson & Hall, 1980). Therefore, it appears that the study of ingestive behaviors in pups requires both food deprivation and testing in a relatively warm environment. It should be noted, however, that food-deprived pups do not exhibit BAT thermogenesis at subthermoneutral air temperatures (Bignall, Heggeness, & Palmer, 1975; Blumberg & Alberts, 1991), thus suggesting that even an air temperature of 32°C, although relatively warm, is not moderate under experimental conditions that entail food deprivation.

Another behavioral context in which temperature plays an important role is in the development of olfactory preferences for filial huddling in infant rats (Alberts & May, 1984). It was found that during early development, rat pups associate warmth provided by the mother with her characteristic odor, an association that induces olfactory preferences for the odor of littermates by 15 days of age. The development of these olfactory preferences was shown to be associated with the warmth provided by the mother and not with other factors such as suckling. Although Alberts and May interpret their findings within a learning context in which a contingency is established between warmth and maternal odor, it is also possible that the thermal environment plays a permissive role in allowing olfactory preferences to develop. More work is needed to distinguish between these two possibilities.

Changes in heart rate to psychophysical stimuli have been used to infer changes in perceptual and cognitive processing (e.g., Dailey, Wigal, & Amsel, 1986). Hayne, Richardson, and Campbell (1992), however, make the important point that competing physiological demands on cardiac function may influence the expression of the heart rate orienting response, especially in neonates. Noting that air temperature modulates cardiac function, they examined the influence of air temperature on the orienting responses of rat pups exposed to a novel olfactory stimulus. While they found that air temperature had little impact on the behavioral components of the orienting response to a novel odor (e.g., sniffing), cold air temperatures did prevent the expression of the heart rate decelerations that typically accompany the orienting response, especially at the youngest ages tested. Interestingly, comparison of their thermal and heart rate data with ours (e.g., Blumberg et al., 1997) suggests that the heart rate component of the orienting response may only be expressed at moderate and/or thermoneutral air temperatures at which the autonomic nervous system and the cardiovascular system are operating within their normal functional range.

In addition to the air temperature at which testing is performed, it can also be important that pups be given sufficient time to acclimate to a new thermal environment before testing. For example, in our experimental situation, infant rats require as much as 45 min to reach a steady state at a new air temperature. There are, however, experimental questions that focus on the acute behavioral activation of pups that occurs after transfer from the nest to a novel environment (e.g., Noirot, 1968). As Table 2 illustrates for investigations of ultrasound production in infant rats, such “transfer” experiments are characterized by the use of a variety of air temperatures (In fact, in one study, the *younger* pups were exposed to the *colder* air temperature.) Importantly, thermal factors also enter into these experiments through a number of other routes. For example, pups are typically removed from the home cage using bare hands (a source of conductive heat loss) and walked to the novel environment (which adds convective heat loss). In one often-cited study on the olfactory modulation of ultrasound (Oswalt & Meier, 1975), pups in different experimental conditions were placed in metal bowls that were or were not lined with wood shavings. Therefore, in these and other experiments, one is observing a complex interaction between hypothermia, physiological activation, and the focal behavior (Blumberg et al., 1992b).

The effect of removing infant rats from the nesting environment has also been used to examine the short- and long-term effects of maternal deprivation on corticosterone secretion and emotional reactivity (Denenberg, Brumaghim, Haltmeyer, & Zarrow, 1967). As with ultrasound production, it was found that the thermal challenge inherent in the early “handling” paradigms made a substantial contribution to the observed hormonal and behavioral effects (e.g., Denenberg et al., 1967; Schaefer, Weingarten, & Towne, 1962). Not all later studies, however, have adequately controlled for thermal and nonthermal factors. For example, placement of a heating pad beneath the floor of a cage (e.g., Levine, Huchton, Wiener, & Rosenfeld, 1992) may not be sufficient to provide an adequate thermal environment. In contrast, the use of an incubator in which a pup is exposed to a more homogeneous thermal environment provides more reliable information regarding the nonthermally mediated effects of pup separation from the nest (e.g., Kuhn, Pauk, & Schanberg, 1990; Schanberg & Field, 1987).

The natural ecology of the pup also cannot be ignored. The nest, huddle, and mother help to provide a stable thermal environment for the developing pup. Indeed, at an air temperature of 16°C, huddling pups are able to maintain skin temperature at 34°C (Jans & Leon, 1983). In rats, hamsters, and gerbils, huddling is the primary means of thermoregulation within the nest during maternal absence (Alberts, 1978; Leonard, 1974; Schneider, Veltri, DeGraw & French, 1995). When the mother is present, she provides not only milk but also heat to suckling pups (Leon, Coopersmith, Beasley & Sullivan, 1990). In golden hamsters, the mother is present almost constantly during the 1st week postpartum (Leonard, 1974), perhaps a response to the lack of endothermy in the newborns of this species. Therefore, the thermal dimension of the nesting environment is a critical one, and any experimental manipulation of the social environment cannot ignore its thermal implications (Blumberg, Efimova, & Alberts, 1992a).

Finally, in addition to food deprivation, there are a number of experimental manipulations (e.g., surgery, pharmacological treatment) that can disrupt a pup's ability to activate BAT thermogenesis in the cold (e.g., Blumberg & Alberts, 1991). For such experimental manipulations, misinterpretation of results can occur if thermoregulatory responding is not monitored. For example, if a pharmacological or surgical manipulation has the unforeseen effect of inhibiting BAT thermogenesis, then even an air temperature normally considered moderate can produce pronounced hypothermia. In such cases, changes in the dependent variable between the experimental and control groups may arise from an indirect effect of the treatment or manipulation on the pup's ability to produce heat. Therefore, in some experiments, knowing air temperature alone may *not* be enough to draw reliable conclusions regarding an infant's physiological state.

CONCLUSIONS

Over the past 50 years, refinements in theory and methodology have clarified the roles that physiological mechanisms and behavior play in the thermal adaptations of infant mammals. While psychobiologists have championed the importance of behavior as a primary contributor to thermoregulation (Satinoff, 1996), physiologists have elucidated the hormonal, pharmacological, and anatomical features of organisms that contribute to heat production and heat conservation (Nedergaard et al., 1986). From the organism's standpoint, this division of labor between the two disciplines is, at best, artificial (Blessing, 1997); thermoregulation is the product of both behavioral and physiological processes. Building on the contributions of both groups of researchers and the insights outlined in this article, we can begin assessing the interactions between physiology and behavior during development. In addition, our assessments of infant capabilities should be made within a context that acknowledges the differing developmental strategies and ecological niches adopted by different species (Alberts & Cramer, 1988).

Homeostasis is an emergent property of multiple behavioral and physiological components, organized at many levels of the neuraxis (Blumberg, Schalk, & Sokoloff, 1995; Satinoff, 1978), acting in concert and reacting to environmental demands. One current challenge is to understand how homeostasis evolves as these components and the environmental and physical contexts change during development. Moreover, with a more complete understanding of the thermoregulatory capabilities of individual infant rats, we are now better equipped to explore how the individual infant contributes to group regulatory processes in the huddle as well as how the huddle shapes the thermal responses of the individual.

NOTES

We thank Bob Kirby and Evelyn Satinoff for their helpful comments.

REFERENCES

Alberts, J. R. (1978). Huddling by rat pups: Group behavioral mechanisms of temperature regulation and energy conservation. *Journal of Comparative and Physiological Psychology, 92,* 231–245.

Alberts, J. R., & Cramer, C. P. (1988). Ecology and experience: Sources of means and meaning of developmental change. In E. M. Blass (Ed.), *Handbook of behavioral neurobiology, Vol. 8* (pp. 1–39). New York: Plenum Press.

Alberts, J. R., & May, B. (1984). Nonnutritive, thermotactile induction of filial huddling in rat pups. *Developmental Psychobiology, 17,* 161–181.

Altman, J., & Sudarshan, K. (1975). Postnatal development of locomotion in the laboratory rat. *Animal Behaviour, 23,* 896–20.

Baker, M. A. (1979). A brain-cooling system in mammals. *Scientific American, 240,* 130–139.

Bechevalier, J., & Blozovski, D. (1980). Acquisition and retention of classical conditioning in the newborn rat. *Developmental Psychobiology, 13,* 519–526.

Bennett, A. F. (1984). Thermal dependence of muscle function. *American Journal of Physiology, 247,* R217–R229.

Bignall, K. E. (1974). Ontogeny of levels of neural organization: The righting reflex as a model. *Experimental Neurology, 42,* 566–573.

Bignall, K. E., Heggeness, F. W., & Palmer, J. E. (1975). Effect of neonatal decerebration on thermogenesis during starvation and cold exposure in the rat. *Experimental Neurology, 49,* 174–188.

Blessing, W. W. (1997). Inadequate framework for understanding bodily homeostasis. *Trends in Neuroscience, 20,* 235–239.

Block, B. A. (1986). Structure of the brain and eye heater tissue in marlins, sailfish, and spearfishes. *Journal of Morphology, 190,* 169–189.

Block, B. A., & Carey, F. G. (1985). Warm brain and eye temperatures in sharks. *Journal of Comparative Psychology B, 156,* 229–236.

Blumberg, M. S. (1997) Ontogeny of cardiac rate regulation and brown fat thermogenesis in golden hamsters *(Mesocricetus auratus). Journal of Comparative Physiology B, 167,* 552–557.

Blumberg, M. S., & Alberts, J. R. (1990). Ultrasonic vocalizations by rat pups in the cold: An acoustic by-product of laryngeal braking? *Behavioral Neuroscience, 104,* 808–817.

Blumberg, M. S., & Alberts, J. R. (1991). Both hypoxia and milk deprivation diminish metabolic heat production and ultrasound emission by rat pups during cold exposure. *Behavioral Neuroscience, 105,* 1030–1037.

Blumberg, M. S., Efimova, I. V., & Alberts, J. R. (1992a). Ultrasonic vocalizations by rats pups: The primary importance of ambient temperature and the thermal significance of contact comfort. *Developmental Psychobiology, 25,* 229–250.

Blumberg, M. S., Efimova, I. V., & Alberts, J. R. (1992b). Thermogenesis during ultrasonic vocalization by rat pups isolated in a warm environment: A thermographic analysis. *Developmental Psychobiology, 25,* 497–510.

Blumberg, M. S., & Lucas, D. E. (1996). A developmental and component analysis of active sleep. *Developmental Psychobiology, 29,* 1–22.

Blumberg, M. S., Schalk, S. L., & Sokoloff, G. (1995). Pontine and basal forebrain transections disinhibit brown fat thermogenesis in neonatal rats. *Brain Research, 699,* 214–220.

Blumberg, M. S., & Sokoloff, G. (1997). Dynamics of brown fat thermogenesis in week-old rats: Evidence of relative stability during moderate cold exposure. *Physiological Zoology, 70,* 324–330.

Blumberg M. S., & Stolba, M. A. (1996). Thermogenesis, myoclonic twitching, and ultrasonic vocalization in neonatal rats during moderate and extreme cold exposure. *Behavioral Neuroscience, 110,* 305–314.

Blumberg, M. S., Sokoloff, G., & Kirby, R. F. (1997). Brown fat thermogenesis and cardiac rate regulation during cold challenge in infant rats. *American Journal of Physiology, 272,* R1308–R1313.

Brody, E. B. (1943). Development of homeothermy in suckling rats. *American Journal of Physiology, 272,* 230–232.

Brück, K., & Hinckel, P. (1996). Ontogenetic and adaptive adjustments in the thermoregulatory system. In M. J. Fregly & C. M. Blatteis (Eds.), *Handbook of physiology* (pp. 597–611). Oxford: Oxford University Press.

Brück, K., & Wünnenberg, B. (1970). “Meshed” control of two effector systems: Nonshivering and shivering thermogenesis. In J. D. Hardy, A. P. Gagge, & J. A. J. Stolwijk (Eds.), *Physiological and behavioral temperature regulation* (pp. 562–580). Springfield: C. G. Thomas.

Caputa, M. (1984). Some differences in mammalian versus avian temperature regulation: Putative thermal adjustments to flight in birds. In J. R. S. Hales (Ed.), *Thermal physiology* (pp. 413–417). New York: Raven Press.

Carden, S. E., Davachi, L., & Hofer, M. A. (1994). U50,488 increases ultrasonic vocalizations in 3-, 10-, and 18-day-old rat pups in isolation and the home cage. *Developmental Psychobiology, 27,* 65–83.

Carey, F. G. (1982). A brain heater in the swordfish. *Science, 216,* 1327–1329.

Carlson, N. R. (1994). *Physiology of behavior.* Boston: Allyn and Bacon.

Conklin, P., & Heggeness, F. W. (1971). Maturation of temperature homeostasis in the rat. *American Journal of Physiology, 220,* 333–336.

Crawford, E. C., Jr. (1972). Brain and body temperatures in a panting lizard. *Science, 177,* 431–433.

Dailey, W., Wigal., S. B., & Amsel, A. (1986). Effects of photic stimulation on heart rate of infant rats. *International Journal of Psychophysiology, 3,* 183–203.

Daly, M. (1976). Behavioral development in three hamster species. *Developmental Psychobiology, 9,* 315–323.

Dawkins, M. J. R., & Hull, D. (1964). Brown adipose tissue and the response of newborn rabbits to cold. *Journal of Physiology, 172,* 216–238.

Dawson, W. R. (1982). Evaporative losses of water by birds. *Comparative Biochemistry and Physiology, 71A,* 495–509.

Deeming, C., & Ferguson, M. (1989, March 25). In the heat of the nest. *New Scientist, 121,* 33–38.

Denenberg, V. H., Brumaghim, J. T., Haltmeyer, G. C., & Zarrow, M. X. (1967). Increased adrenocortical activity in the neonatal rat following handling. *Endocrinology, 81,* 1047–1052.

DeVries, A. L. (1982). Biological antifreeze agents in cold water fishes. *Comparative Biochemistry and Physiology, 73A,* 627–640.

Fairfield, J. (1948). Effects of cold on infant rats: Body temperatures, oxygen consumption, electrocardiograms. *American Journal of Physiology, 155,* 355–365.

Fowler, S. J., & Kellogg, C. (1975). Ontogeny of thermoregulatory mechanisms in the rat. *Journal of Comparative and Physiological Psychology, 89L,* 738–746.

Gaunt, S. L. L. (1980). Thermoregulation in doves *(Columbidae):* A novel esophageal heat exchanger. *Science, 210,* 445–447.

Goodwin, G. A., Molina, V. A., & Spear, L. P. (1994). Repeated exposure of rat pups to isolation attenuates isolation-induced ultrasonic vocalization rates: Reversal with naltrexone. *Developmental Psychobiology, 27,* 53–64.

Gramsbergen, A., Schwartze, P., & Prechtl, H. F. R. (1970). The postnatal development of behavioral states in the rat. *Developmental Psychobiology, 3,* 267–280.

Hahn, P. (1956). The development of thermoregulation. III. The significance of fur in the development of thermoregulation in rats. *Physiologia Bohemoslovenica, 5,* 428–431.

Hayne, H., Richardson, R., & Campbell, B. (1992). Developmental contraints on the expression of behavioral and heart rate orienting responses: II. The role of ambient temperature. *Developmental Psychobiology, 25,* 51–65.

Heath, J. E. (1966). Venous shunts in the cephalic sinuses of horned lizards. *Physiological Zoology, 39,* 30–35.

Heikkila, J. J., & Brown, I. R. (1979). Hyperthermia and disaggregation of brain polysomes induced by bacterial pyrogen. *Life Sciences, 25,* 347–352.

Heim, T., & Hull, D. (1966). The blood flow and oxygen consumption of brown adipose tissue in the newborn rabbit. *Journal of Physiology, 186,* 42–55.

Heinrich, B. (1979). Keeping a cool head: Honeybee thermoregulation. *Science, 205,* 1269–1271.

Heinrich, B. (1987). Thermoregulation by winter-flying endothermic moths. *Journal of Experimental Biology, 127,* 313–332.

Heinrich, B. (1993). *The hot-blooded insects: Strategies and mechanisms of thermoregulation.* Cambridge: Harvard University Press.

Hissa, R. (1968). Postnatal development of thermoregulation in the Norwegian lemming and the golden hamster. *Annoles Zoologici Fennici, 5,* 345–383.

Hofer, M. A., & Shair, H. (1978). Ultrasonic vocalization during social interaction and isolation in 2-week-old rats. *Developmental Psychobiology, 11,* 495–504.

Houk, J. C. (1988). Control strategies in physiological systems. *FASEB Journal, 2,* 97–107.

Hsieh, A. C. L., Carlson, L. D., & Gray, G. (1957). Role of the sympathetic nervous system in the control of chemical regulation of heat production. *American Journal of Physiology, 190,* 247–251.

Hull, D., & Segall, M. M. (1965). The contribution of brown adipose tissue to heat production in the newborn rabbit. *Journal of Physiology, 181,* 449–457.

IUPS Thermal Commission. (1987). Glossary of terms for thermal physiology. *Pflügers Archive, 410,* 567–587.

Jans, J. E., & Leon, M. (1983). Determinants of mother–young contact in Norway rats. *Physiology & Behavior, 30,* 919–935.

Johanson, I. B. (1979). Thermotaxis in neonatal rat pups. *Physiology & Behavior, 23,* 871–874.

Johanson, I. B., & Hall, W. G. (1979). Appetitive learning in 1-day-old rat pups. *Science, 205,* 419–421.

Johanson, I. B., & Hall, W. G. (1980). The ontogeny of feeding in rats: III. Thermal determinants of early ingestive responding. *Journal of Comparative and Physiological Psychology, 94,* 977–992.

Jouvet-Mounier, D., Astic, L., & Lacote, D. (1970). Ontogenesis of the states of sleep in rat, cat, and guinea pig during the first postnatal month. *Developmental Psychobiology, 2,* 216–239.

Kelso J. A. S. (1995). *Dynamic patterns: The self-organization of brain and behavior.* Cambridge: MIT Press.

Kilgore, D. L., Jr., Bernstein, M. H., & Hudson, D. M. (1976). Brain temperature in birds. *Journal of Comparative Physiology, 110,* 209–215.

Kirby, R. F., & Blumberg, M. S. (1998). Maintenance of arterial pressure in infant rats during moderate and extreme thermal challenge. *Developmental Psychobiology, 32,* 169–176.

Kleitman, N., & Satinoff, E. (1982). Thermoregulatory behavior in rat pups from birth to weaning. *Physiology & Behavior, 29,* 537–541.

Kuhn, C. M., Pauk, J., & Schanberg, S. M. (1990). Endocrine responses to mother–infant separation in developing rats. *Developmental Psychobiology, 23,* 395–410.

LaPointe, G., & Nosal, G. (1979). The postnatal evolution of muscular twitches in the developing rat. *Experientia, 35,* 1070–1072.

Leon, M. (1986). Development of thermoregulation. In E. M. Blass (Ed.), *Handbook of behavioral neurobiology, vol. 8* (pp. 297–322). New York: Plenum Press.

Leon, M., Coopersmith, R., Beasley, L. J. & Sullivan, R. M. (1990). Thermal aspects of parenting. In N. A. Krasnegor & R. S. Bridges (Eds.), *Mammalian parenting: Biochemical, neurobiological and behavioral determinants* (pp. 400–415). New York: Oxford University Press.

Leonard, C. M. (1974). Thermotaxis in golden hamster pups. *Journal of Comparative and Physiological Psychology, 86,* 458–469.

Leonard, C. M. (1982). Shifting strategies for behavioral thermoregulation in developing golden hamsters. *Journal of Comparative and Physiological Psychology, 96,* 234–243.

Levine, S., Huchton, D. M., Wiener, S. G., & Rosenfeld, P. (1992). Time course of the effect of maternal deprivation on the hypothalamic–pituitary–adrenal axis in the infant rat. *Developmental Psychobiology, 24,* 547–558.

Linthicum, D. S., & Carey, F. G. (1972). Regulation of brain and eye temperatures by the bluefin tuna. *Comparative Biochemistry and Physiology, 43A,* 425–433.

Lyman, C. P., & Blinks, D. C. (1959). The effect of temperature on the isolated hearts of closely related hibernators and nonhibernators. *Journal of Cellular and Comparative Physiology, 54,* 53–63.

Martin, L. T., & Alberts, J. R. (1982). Associative learning in neonatal rats revealed by cardiac response patterns. *Journal of Comparative and Physiological Psychology, 96,* 668–675.

Millan, N., Murdock, L. L., Bleier, R., & Siegel, F. L. (1979). Effects of acute hyperthermia on polyribosomes in-vivo protein synthesis and ornithine decarboxylase activity in the neonatal rat brain. *Journal of Neurochemistry, 32,* 311–317.

Miller, J. S., Molina, J. C., & Spear, N. E. (1990). Ontogenetic differences in the expression of odor aversion learning in 4- and 8-day-old rats. *Developmental Psychobiology, 23,* 319–330.

Moran, T. H., Lew, Mark F., & Blass, E. M. (1981). Intracranial self-stimulation in 3-day-old rat pups. *Science, 214,* 1366–1368.

Mrosovsky, N. (1990). *Rheostasis: The physiology of change.* Oxford: Oxford University Press.

Naito, H., & Tonoue, T. (1987). Sex difference in ultrasound distress call by rat pups. *Behavioural Brain Research, 25,* 13–21.

Nedergaard, J., Connolly, E., & Cannon, B. (1986). Brown adipose tissue in the mammalian neonate. In P. Trayhurn & D. G. Nicholls (Eds.), *Brown adipose tissue* (pp. 152–213). London: Edward Arnold.

Noirot, E. (1968). Ultrasounds in young rodents. II. Changes with age in albino rats. *Animal Behaviour, 16,* 129–134.

Okon, E. E. (1971). The temperature relations of vocalization in infant golden hamsters and Wistar rats. *Journal of Zoology, London, 164,* 227–237.

Oswalt, G. L., & Meier, G. W. (1975). Olfactory, thermal, and tactual influences on infantile ultrasonic volcalization in rats. *Developmental Psychobiology, 8,* 129–135.

Pinshow, B., Bernstein, M. H., Lopez, G. E., & Kleinhaus, S. (1982). Regulation of brain temperature in pigeons: Effects of corneal convection. *American Journal of Physiology, 242,* R577–R581.

Rosenzweig, M. R., Leiman, A. L., & Breedlove, S. M. (1996). *Biological psychology*. Sunderland, MA: Sinauer.

Satinoff E. (1978). Neural organization and evolution of thermal regulation in mammals. *Science, 201,* 16–22.

Satinoff, E. (1991). Developmental aspects of behavioral and reflexive thermoregulation. In H. N. Shair, G. A. Barr, & M. A. Hofer (Eds.), *Developmental psychobiology: New methods and changing concepts* (pp. 169–188). Oxford: Oxford University Press.

Satinoff, E. (1996). Behavioral thermoregulation in the cold. In M. J. Fregly & C. M. Blatteis (Eds.), *Handbook of physiology* (pp. 481–505). Oxford: Oxford University Press.

Schaefer, T., Weingarten, F. S., & Towne, J. C. (1962). Temperature change: The basic variable in the early handling phenomenon? *Science, 125,* 41–42.

Schanberg, S. M., & Field, T. M. (1987). Sensory deprivation stress and supplemental stimulation in the rat pup and preterm human neonate. *Child Development, 58,* 1431–1447.

Schmidt-Nielsen, K. (1990). *Animal physiology*. Cambridge: Cambridge University Press.

Schneider, J. R., Veltri, A. M., DeGraw, W. A. & French, J. A. (1995). Telemetered temperature in preweanling Mongolian gerbils *(Meriones unguiculatus). Physiology & Behavior, 57,* 199–203.

Schoenfeld, T. A., & Leonard, C. M. (1985). Behavioral development in the Syrian golden hamster. In H. I. Siegel (Ed.), *The hamster: Reproduction and behavior* (pp. 289–321). New York: Plenum Press.

Smith, R. E. (1964). Thermoregulatory and adaptive behavior of brown adipose tissue. *Science, 146,* 1686–1689.

Smith, R. E., & Horwitz, B. A. (1969). Brown fat and thermogenesis. *Physiological Reviews, 49,* 330–425.

Smith, R. E., & Roberts, J. C. (1964). Thermogenesis of brown adipose tissue in cold-acclimated rats. *American Journal of Physiology, 206,* 143–148.

Sokoloff, G., & Blumberg, M. S. (1997). Thermogenic, respiratory, and ultrasonic responses of week-old rats across the transition from moderate to extreme cold exposure. *Developmental Psychobiology, 30,* 181–194.

Sokoloff, G., & Blumberg, M. S. (1998). Active sleep in cold-exposed infant Norway rats and Syrian golden hamsters. The role of brown adipose tissue thermogenesis. *Behavioral Neuroscience, 112,* 695–706.

Sokoloff, G., Kirby, R. F., & Blumberg, M. S. (in press). Further evidence that BAT thermogenesis modulates cardiac rate in infant rats. *American Journal of Physiology.*

Spiers, D. E., & Adair, E. R. (1986). Ontogeny of homeothermy in the immature rat: Metabolic and thermal responses. *Journal of Applied Physiology, 60,* 1190–1197.

Swadlow, H. A., Waxman, S. G., & Weyand, T. G. (1981). Effects of variations in temperature on impulse conduction along nonmyelinated axons in the mammalian brain. *Experimental Neurology, 71,* 383–389.

Swithers-Mulvey, S. E., Miller, G. L., & Hall, W. G. (1991). Habituation of oromotor responding to oral infusions in rat pups. *Appetite, 17,* 55–67.

Takano, N., Mohri, M., & Nagasaka, T. (1979). Body temperature and oxygen consumption of newborn rats at various ambient temperatures. *Japanese Journal of Physiology, 29,* 173–180.

Taylor, C. R., & Lyman, C. P. (1972). Heat storage in running antelopes: Independence of brain and body temperatures. *American Journal of Physiology, 222,* 114–117.

Taylor P. M. (1960). Oxygen consumption in newborn rats. *Journal of Physiology, 154,* 153–168.

Teitel, D. F., Sidi, D., Chin, T., Brett, C., Heymann, M. A., & Rudolph, A. M. (1985). Developmental changes in myocardial contractile reserve in the lamb. *Pediatric Research, 19,* 948–955.

Van Someren, E. J. W., Mirmiran, M., Bos, N. P. A., Lamur, A., Kumar, A., & Molenaar, P. C. M. (1990). Quantitative analysis of eye movements during REM-sleep in developing rats. *Developmental Psychobiology, 23,* 55–61.

Weber, E. D., & Stelzner, D. J. (1977). Behavioral effects of spinal cord transection in the developing rat. *Brain Research,* 125, 241–255.