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COMMENTARIES

The Amygdala and Development of Social Cognition: Theoretical Comment on Bauman, Toscano, Mason, Lavenex, and Amaral (2006)

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Nonhuman primate studies, using selective amygdala lesions that spare cortical areas and fibers of passage, have helped to clarify the amygdala's specific contribution to social and emotional behavior. M. D. Bauman, J. E. Toscano, W. A. Mason, P. Lavenex, and D. G. Amaral (2006) reported that macaque monkeys (*Macaca mulatta*) with neonatal neurotoxic amygdala lesions displayed lower rank in social dominance status, reduced aggressive gestures, and enhanced fearful reactions to social cues compared with normal controls and those with neonatal hippocampal lesions when tested as juveniles in a group of peers. These results are discussed in light of a recent study (C. J. Machado & J. Bachevalier, 2006) showing that the same selective amygdala damage in adolescent monkeys did not alter presurgical social dominance status. This variability in behavioral changes after selective amygdala lesions underscores the significant interplay between timing of the lesion, genetic traits, and environmental factors and suggests that the amygdala is not the generator of specific emotional responses, but acts as a modulator to ensure that emotional responses are appropriate to the external stimuli and social context.

Keywords: social dominance, fear, anxiety, neurotoxic lesions, monkeys

Klüver and Bucy's (1939) cornerstone studies imprinted very early the idea of a link between the primate temporal lobe and socioemotional cognition. Subsequent lesion studies in monkeys, based on nonselective ablation or radio frequency techniques, were instrumental to identifying the amygdala as the critical region responsible for a wide spectrum of disorders (encompassing emotion and social behavior but also many forms of learning and memory). Decisive progress in this field has been tightly linked to technical refinements of surgical and histological procedures. The application to the monkey of selective neurotoxic lesions together with more recent development of reversible lesions produced by intracerebral injection of agents transiently blocking neural activity has narrowed the spectrum of amygdala functions down to the social–emotional domain, whereas learning and memory processes—for example, object recognition and stimulus–stimulus associative memory—that were linked previously to amygdala functions have now been attributed to the cortical areas adjacent to the amygdala (Málková, Gaffan, & Murray, 1997; Meunier, Bachevalier, Mishkin, & Murray, 1993; Murray, Gaffan, & Mishkin, 1993). Thus, neurotoxic amygdala lesions converge with earlier results after temporal lobectomies or amygdalectomies to indicate that the disorders most frequently seen in adult laboratory monkeys (mostly males and observed alone or in dyads) consist of reduced fear and aggression together with excessive and indiscriminate object exploration (manual and/or oral) and a loss of social affiliation (Emery et al., 2001; Izquierdo, Suda, & Murray, 2005; Kalin, Shelton, Davidson, & Kelley, 2001; Meunier, Bachevalier, Murray, Málková, & Mishkin, 1999; Stefanacci, Clark, & Zola, 2003). Moreover, unilateral gamma aminobutyric acid alpha receptors' blockade of the amygdala suffices to produce a temporary breakdown of dyadic social interactions (Málková, Barrow, Lower, & Gale, 2003). The contour of amygdala functions in adult monkeys having now been considerably clarified, the time is now ripe for progress on a still elusive issue, namely, how best to characterize the amygdala contribution to the development of the social brain.

In this domain, the data are still limited to only a few studies. Earlier reports (Bachevalier, 1994; Thompson, 1981) indicated that neonatal aspiration lesions of the amygdala in peer-reared infant monkeys yielded changes in socioemotional behaviors that became increasingly evident when the monkeys reached adulthood. More recently, a series of studies followed in greater detail the long-term effects of neonatal damage of the amygdala, by using selective neurotoxic lesions in monkeys reared by their biological mother until the age of 6 months and placed in small social groups thereafter (Bauman, Lavenex, Mason, Capitanio, & Amaral, 2004; Prather et al., 2001). Although selective neonatal amygdala damage did not affect the production of social responses, it did increase fearful gestures and behaviors during social encounters, specifically when the operated monkeys were face to face with other monkeys in the group. In contrast, the operated monkeys were less fearful than sham-operated monkeys when presented with novel objects and stimuli. The article by Bauman,

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Toscano, Mason, Lavenex, and Amaral (2006) published in this issue of *Behavioral Neuroscience* represents another attempt to clarify the impact of neonatal neurotoxic amygdala lesions on social behavior, this time on the expression of social dominance.

The authors compared social dominance status in juvenile (approximately 18-month-old) rhesus monkeys (*Macaca mulatta*) that had sustained bilateral neurotoxic damage of the amygdala or the hippocampus or sham operations at 2 weeks of age. These monkeys were reared with their biological mother until they were weaned at 6 months of age, after which they were placed permanently in social groups that included 2 monkeys of each lesion type. Species-typical dominance behavior among the 6 members of the social group was assessed by competition for a limited food source. Compared with hippocampal- and sham-operated monkeys, those with amygdala lesions displayed lower ranking on all indices of social dominance (e.g., less frequent initial access and longer latency to the food) as well as a diminished capacity to use species-specific aggressive behaviors. In addition, heightened fear responses to social partners were still present. Relying on a recent model of social dominance requiring the interplay between both agonistic and affiliative social signals, Bauman et al. (2006) suggest that the lack of initiation of aggressive signals is likely to prevent the amygdala-operated monkeys from gaining higher social rank in their group.

As noted by Bauman et al. (2006), their findings parallel those reported earlier by Thompson (1981) indicating increased submissive behaviors following neonatal aspiration lesion of the amygdala. Because in the case of Thompson's studies the monkeys were peer reared and amygdala lesions also included a portion of the adjacent temporal cortical areas as well as fibers from these cortical areas coursing in and around the amygdala, Bauman et al.'s findings clearly indicate that damage limited to the amygdaloid nuclei is sufficient to produce the decline in social rank. The findings are also consistent with the fall in social dominance generally found in adult monkeys with aspiration lesions of the amygdala when reintroduced into their social groups (Kling & Cornell, 1971; Plotnik, 1968; Rosvold, Mirsky, & Pribram, 1954). However, all these earlier studies in adult monkeys used nonselective lesions, sometimes involving the entire anterior temporal lobe, and the question of whether more selective amygdala lesions performed in mature animals will result in drastic changes in dominant status has not been so far answered conclusively.

There are at present only two studies that have investigated the effects of selective amygdala lesions in adult monkeys on social interactions. In the first (Emery et al., 2001), operated middle-ranking male monkeys (5–7 years of age) underwent a series of 10- to 20-min sessions during which they were first placed near and then together with a relatively unfamiliar partner. In all conditions, the operated subjects displayed no aggressive gestures or behaviors but were instead overly affiliative. Although no aberrant sexual behaviors were noted, hyperorality was present. This unbridled approach was indiscriminately initiated toward operated and normal peers alike. Operated animals thus globally demonstrated none of the initial tension or wariness that monkeys usually show when confronted with an unfamiliar, and hence potentially dangerous, conspecific. Although these findings constituted the first evidence that selective amygdala damage is sufficient to disrupt actual social interactions, the authors acknowledged, however, that in light of the marked differences seen earlier by Rosvold et al. (1954) and Kling and Brothers (1992) across social contexts, the specific change they observed during these brief dyadic encounters (decreased social fear) may not generalize to more demanding social situations. In addition, this study did not specifically assess the dominance status of the monkeys.

A more recent study on the effects of selective amygdala, orbital frontal cortex, and hippocampal lesions on social behaviors in young adult (adolescent) monkeys (Machado & Bachevalier, 2006) found no measurable changes in the social status after amygdala lesions when the subjects were reintroduced into their social group. In this later study, personality ratings, social and nonsocial behaviors, and social dominance status were evaluated in groups of 4 monkeys (3 years of age) both prior to and following lesions of the three brain areas. The study was specifically designed such that each experimental group was balanced with respect to presurgical dominance rank, and dominance status was measured both by identifying the linear dominance hierarchy of each monkey in the group during social interaction and by a food competition procedure (Mirsky, 1960) during which food pellets were introduced in one of three food wells at a rate of one pellet per minute. Both subordinate and dominant monkeys with amygdala lesions regained their presurgical social hierarchy status despite their tendency to display more aggressive signals (crooktail), indicating that these aggressive signals were not acknowledged by the other members of the group. Thus, although these results contrasted with the increased affiliative behaviors reported earlier by Emery et al. (2001), the differences are likely to have emerged from different procedural methods, such as the complexity of social contexts and the familiarity of social partners prior to surgery, as well as the age of the monkeys. Because the latter study (Machado & Bachevalier, 2006) used adolescent males that were not at the age of 3 years fully mature (male rhesus macaques reach maturity at 4–5 years; Mann, Akinbami, Gould, Paul, & Wallen, 1998), there is still a possibility that neurotoxic lesions in fully mature animals exposed to a similarly complex environment may yield different results. However, neither study demonstrated the fall of dominant rank generally reported after extensive amygdala damage or neonatal selective damage to the amygdala. Although it is tempting to speculate that effects of neonatal amygdala damage might result in different behavioral outcomes than late lesions, future studies will need to determine whether selective amygdala lesions in adult monkeys, like those performed neonatally, eventually lead to the opposite change—that is, subordination—when the monkeys are faced with the long-lasting challenge of a complex social environment.

As mentioned by Bauman et al. (2006), selective amygdala lesions in monkeys are also generally associated with the processing of fear responses. It is interesting to note, however, that although the present results indicate heightened levels of fear signals in the presence of social partners, data from other recent reports (Izquierdo et al., 2005; Kalin, Shelton, & Davidson, 2004; Kalin et al., 2001; Meunier et al., 1999; Stefanacci et al., 2003) showed an opposite pattern of changes, namely, a decrease in fear reactions (as measured by defensive and approach responses) when faced with social stimuli (human intruder). Again, several possible factors could have led to such divergent results. As discussed above, one factor relates to the social context in which the effects of selective amygdala lesions were investigated, that is, active social interactions with peers in the case of the Bauman et

al. (2006) study compared with a human intruder in the earlier studies referred to above. In this regard, it is interesting to note that in the recent study by Machado and Bachevalier (2006), the monkeys with selective amygdala lesions, like those in the Bauman et al. (2006) study, displayed increased anxious behaviors after being reintroduced into their familiar social groups after surgery, suggesting that the complexity of the environment is likely to modulate the changes in fear responses produced by monkeys with amygdala lesions. Yet, another factor that needs to be considered is the age at which the lesions were performed—that is, in infancy in the case of Bauman et al. (2006) and in adolescence in the case of Machado and Bachevalier (2006), rather than in adulthood in the previous studies.

The foregoing discussion underscores the need to better investigate the interplay between genetic traits and environmental factors (rearing conditions, social contexts) as well as timing of the lesions (infancy, adolescence, or adulthood) when investigating the effects of amygdala damage on social behavior and emotional reactions. The studies initiated by this group of investigators clearly constitute a significant contribution to the literature on the functional ontogeny of the amygdala in primate social behavior. Although the article does not answer all of the questions about the time course and milestones of functional amygdala development, it goes a long way toward demonstrating that the development of certain aspects of social skills requires the integrity of the amygdala, and it contributes substantially to our knowledge of the development of behavioral and cognitive functions in nonhuman primate models.

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