

Corticosterone and memory in birds

V V Pravosudov

Department of Psychology, University of California, Davis, CA 95616, USA

Introduction

The relationship between stress, glucocorticoid hormones and memory has received much attention in mammalian studies (10, 11, 28). It is generally assumed that while short-term elevation of stress hormones could be beneficial for memory, prolonged elevation has deleterious effects on cognitive abilities of animals (10, 11, 28). Avian studies of stress hormones have mostly concentrated on the relationship between adverse environmental conditions and corticosterone, and the effects of stress-induced corticosterone levels on behavior and physiology (36, 37). The relationship between corticosterone and memory has not received much attention. Memory is an important mechanism by which all animals acquire and retain information about the surrounding environment and it is critically important for existence and survival. Therefore, to fully understand the impact of stress hormones on fitness consequences in birds, we need to investigate the effects of naturally occurring variation in corticosterone on memory.

Available data on the relationship between corticosterone and memory in birds are scarce but suggest that corticosterone plays an important role in memory formation (8, 26, 27). Using domestic chicks as a model, it has been demonstrated that administration of moderate, but not high, corticosterone doses enhanced memory for a weak aversant in a passive avoidance task (26), whereas blocking glucocorticoid synthesis impaired memory performance (8). However, in a task involving a strong aversant, both moderate and high doses of administered corticosterone impaired memory retention (26). In greylag goose goslings (*Anser anser*), better learning performance was correlated with higher levels of excreted corticosterone (12). Another study reported that rapid short-term corticosterone elevations enhanced spatial memory performance and increased cache retrieval efficiency in food caching mountain chickadees (*Poecile gambeli*, 25). Unfortunately, it is hard to evaluate the results of this study because it appears that corticosterone levels were experimentally elevated well above naturally occurring

maximum stress-induced corticosterone levels reported for this species. These authors used a noninvasive corticosterone treatment, following the study of white-crowned sparrows (*Zonotrichia leucophrys*) by Breuner *et al.* (1), which rapidly resulted in corticosterone increase to about 100 ng/ml (1). Several studies of mountain chickadees showed that they did not reach such high corticosterone levels even during standardized stress-response tests (19, 20, 22). In addition, white-crowned sparrows weigh about twice as much as mountain chickadees and the effect of the same corticosterone dose used in the white-crowned sparrows study would have likely produced much stronger effect in mountain chickadees. Thus, it remains to be examined whether high corticosterone levels within the range experienced by these birds during adrenocortical response to acute stress have an effect on spatial memory.

Here I discuss the relationship between prolonged but moderate elevations in plasma corticosterone and spatial memory within the context of natural history in food-caching birds.

Long-term moderate corticosterone elevation

The benefits of short-term corticosterone elevation in response to adverse changes in the environment are well known, but prolonged corticosterone elevations are generally considered harmful (10, 11, 28, 36, 37). However, it appears that some birds may maintain moderately elevated corticosterone levels for fairly long periods of time. For example, food-caching willow tits (*Parus montanus*) appear to maintain moderately elevated baseline corticosterone for several months (Fig. 1).

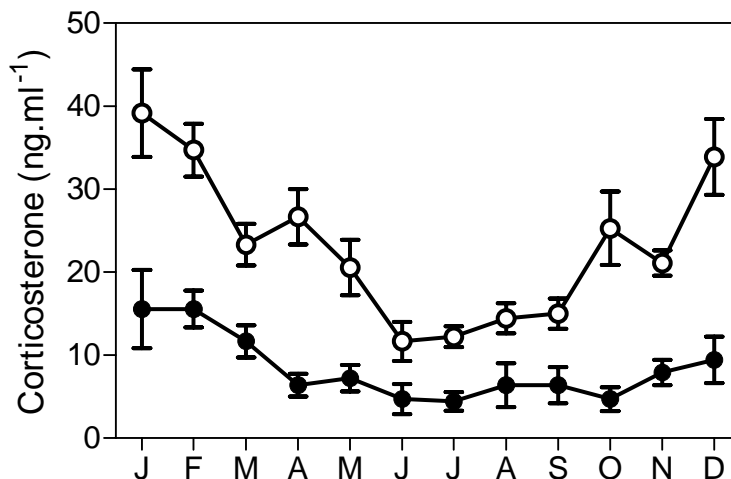


Fig. 1 Seasonal changes in baseline (filled circles) and stress-induced (open circles) plasma corticosterone levels in free-ranging willow tits in Sweden (data from 33).

It seems that the period during which baseline corticosterone levels were elevated coincided with winter months when these birds usually experience their most challenging environmental conditions due to limited and unpredictable food supply, low ambient temperature, persistent snow cover and short days available to foraging. Elevated corticosterone levels in willow tits were registered for *ca.* 5 months – from November until March. These elevations in baseline corticosterone were only moderate as they exceeded the summer lowest levels by only 2-3 times. Stress-induced levels, on the other hand are usually much higher and they can exceed baseline more than 10 times (19, 20, 22, 33). It appears that stress-induced corticosterone levels also varied seasonally in willow tits (Fig. 1). During the summer, however, stress-induced corticosterone levels in willow tits were lowest, lower even than baseline levels experienced during winter (Fig. 1).

Long-term limited unpredictable food and corticosterone

Several environmental factors could potentially cause moderate corticosterone elevation in wintering birds and only experiments can establish the role of each one of them. For example, when food was unlimited, baseline corticosterone levels of mountain chickadees maintained on short, winter-like days in a laboratory were indistinguishable from those of chickadees maintained on long, summer-like days (20). Poor foraging conditions, on the other hand, seem to be sufficient to cause moderate, but significant elevation in baseline corticosterone levels in food-caching mountain chickadees (Fig 2A) and these changes resemble those observed in willow tits (33).

It is well known that short-term food deprivation elicits corticosterone elevation in birds (7, 9). But in natural conditions, resident birds may experience poor foraging conditions for several months during the winter and thus corticosterone levels may remain elevated over extended periods of time (33). Supporting this view, baseline corticosterone levels of mountain chickadees maintained on limited and unpredictable food supply for over 90 days were significantly higher than those of chickadees maintained on *ad libitum* food (Fig. 2A). Such an increase in corticosterone levels was only moderate and elevated levels were much smaller than stress-induced corticosterone levels (Fig. 2B). The effect of food supply was limited to baseline corticosterone only and there were no differences in a magnitude of the adrenocortical response to acute stress between birds maintained on limited and unpredictable food supply and birds maintained on *ad libitum* food (Fig. 2B). Interestingly, in free-ranging willow tits stress-induced levels also vary seasonally similarly to the baseline values and highest stress-induced levels coincided with the highest baseline corticosterone levels

(Fig. 1). Laboratory experiments with mountain chickadees showed that food supply did not affect stress-induced levels and thus, some other factors must be responsible for the seasonal variation in stress-induced corticosterone levels observed in willow tits (33).

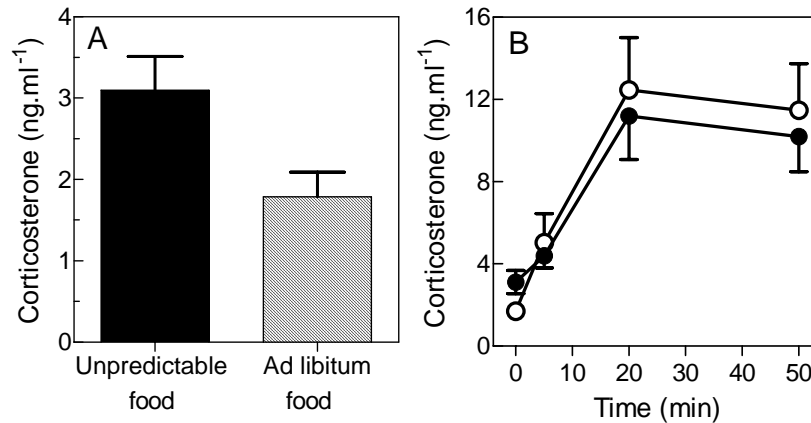


Fig. 2 Plasma corticosterone levels in mountain chickadees maintained on limited and unpredictable food supply (solid bar and filled circles) and on *ad libitum* food supply (hatched bar and open circles). A. Baseline corticosterone levels; B. Adrenocortical response to acute stress. Columns and points represent mean \pm SE (data from 19).

Thus, experimental data on mountain chickadees suggest that baseline corticosterone levels may remain elevated for prolonged periods of time in resident birds experiencing poor foraging conditions. Further support for this finding comes from a study showing that baseline plasma corticosterone levels in red knots (*Calidris canutus*) maintained on a variable feeding schedule were significantly higher compared to plasma levels in knots maintained on a constant feeding schedule (23). While the exact timing of the experimental feeding schedules was unfortunately not presented in the paper, it appears that the treatments lasted for about a month. Therefore, this study also suggested that birds might maintain moderately elevated baseline corticosterone levels for extended periods of time during unpredictable foraging conditions. It is widely believed that prolonged or chronic elevation in glucocorticoid levels has harmful effects on animals' health (10, 11, 28). The experiments with mountain chickadees and red knots, on the other hand, suggest that some animals may routinely experience extended periods of moderate corticosterone elevations in adverse natural conditions and such a response may be adaptive (19, 23).

The benefits of short-term increases in corticosterone in response to sudden changes in environmental conditions are well described (36,

37) and include re-direction of behavior and physiology towards immediate survival. In particular, elevated corticosterone might trigger opportunistic migration and facilitate the mobilization of stored energy reserves (36, 37). But resident birds, such as food-caching willow tits, usually do not leave their home ranges during the winter and even experimentally increased levels of corticosterone failed to trigger migratory movements in these birds during the winter (32). Instead, it appears that corticosterone elevation might facilitate behaviors that increase survival without the birds moving to more favorable locations, such as exploratory behavior, feeding, food caching, and enhanced spatial memory needed for successful cache retrieval. Unlike short-term strong responses to acute stress, adrenocortical responses to typical harsh winter conditions might involve only moderate elevations in baseline corticosterone, which may last for a relatively long time (weeks or even months). While maintaining even moderately elevated corticosterone levels might have costs (e.g. a suppressed immune response), the benefits of such elevations likely outweigh these costs.

Long-term limited and unpredictable food and memory.

During the winter, resident birds have to accumulate enough energy reserves to survive long cold nights and thus foraging proficiency should be crucial for their survival. Food-caching birds, such as willow tits or mountain chickadees, scatter-ward numerous food caches around their territory during the time when food is available and then rely on these food caches when natural food is scarce (35). Whereas these birds create most of their caches during late summer and autumn when natural food is abundant, they continue caching even during the winter (13). It is not clear whether winter caching consists of finding and storing new food items or whether these birds simply re-cache food stores created previously (13, 16). In either case, these food caches are mostly important during the winter when resident birds face the greatest energetic challenges (16). To benefit from caches, food-caching birds have to successfully recover them and spatial memory has been implicated as one of the mechanisms used for cache retrieval (31).

Fitness consequences of better memory may not be equal throughout the year; forgetting cache locations during periods with plenty of naturally occurring food might not yield the same costs as forgetting locations of food caches during energetically demanding periods such as winter, when natural food is scarce. Indeed, mountain chickadees maintained on limited and unpredictable feeding schedule retrieved their caches more accurately and performed better on spatial memory tests than chickadees maintained on *ad libitum* food (Fig. 3). Thus, chickadees experiencing long-term limited and unpredictable food

supply had moderately but significantly elevated corticosterone levels and they also demonstrated better spatial memory performance compared to the birds maintained on *ad libitum* food. These results suggest that elevation in baseline corticosterone could have been responsible for improved spatial memory performance.

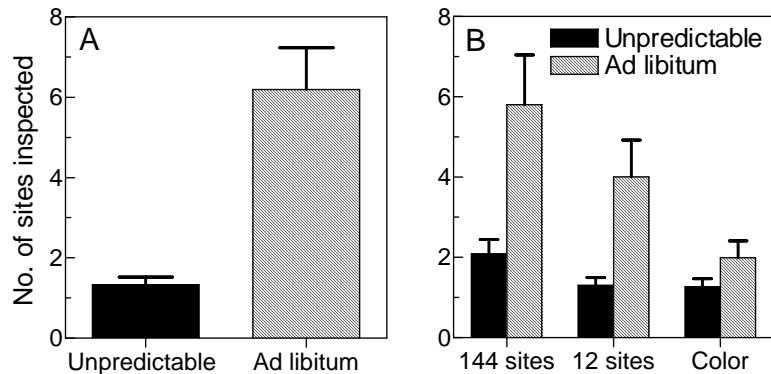


Fig. 3 Performance of mountain chickadees maintained on limited and unpredictable (filled bars) and on *ad libitum* (hatched bars) food supply in a cache-recovery (A) and in a one-trial associative learning task (B). Memory performance was measured as the number of sites inspected in order to find previously hidden caches (cache-recovery task) or the site previously containing food (one-trial associative learning task). During a one-trial associative learning task, birds had to search for the site previously containing food either among 144 or 12 available sites. Fewer sites inspected indicate better memory performance. To investigate whether the differences found between the experimental groups were mainly due to differences in spatial memory and not in motivation to search, a color version of a one-trial associative learning task was performed in which a single site (of 12 available sites) containing food was marked with a unique color. The color task suggested that motivational differences were unlikely because there were no significant differences between the two groups of birds in the number of searches to find the color-marked site. This result suggested that the differences were specific to spatial memory. Columns represent mean \pm SE (data from 15).

Long-term corticosterone elevation and memory

The effect of glucocorticoid stress hormones on memory has received much attention in mammalian studies (10, 11, 28). Generally, they suggest that short-term elevation in these hormones could be highly beneficial for memory while any prolonged, chronic elevation usually results in memory impairments (10, 11, 28).

In food-caching mountain chickadees, it was found that long-term limited and unpredictable food supplies resulted in enhanced spatial

memory and in moderate but significant corticosterone elevation (Fig. 2). These data, however, provide only a correlational link between elevated corticosterone and enhanced spatial memory.

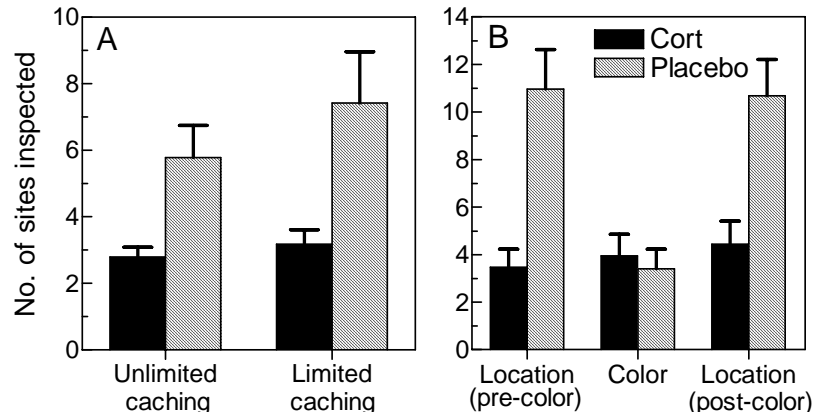


Fig. 4 Performance of corticosterone- (solid bars) and placebo-implanted (hatched bars) mountain chickadees in a cache-retrieval task (A) and in a one-trial associative learning task (B). Columns represent mean \pm SE. During unlimited caching trials, birds were not restricted in the amount of caching and corticosterone-implanted birds cached significantly more seeds than placebo-implanted individuals. During limited caching trials caching was restricted to three caches in all birds. Memory performance was measured as the number of sites inspected in order to find previously hidden caches (cache-recovery task) or the site previously containing food (one-trial associative learning task). Fewer sites inspected indicate better memory performance. To investigate whether the differences found between the experimental groups were mainly due to differences in spatial memory and not in motivation to search, a color version of a one-trial associative learning task was performed in which a site containing food was marked with a unique color. The color task suggested that motivational differences were unlikely because there were no significant differences between the two groups of birds in the number of searches to find the color-marked site. The differences between corticosterone- and placebo-implanted birds re-appeared when the color task was followed by a spatial task reinforcing the conclusion that the differences between the groups were specific to spatial memory (data from 14).

To establish a causal link between moderately elevated corticosterone and spatial memory, mountain chickadees were implanted with 90-day continuous time release biodegradable implants containing 0.075 mg of corticosterone and tested on spatial memory tests starting on 7th and ending on 48th day after implantation (14). Such implants result in moderate corticosterone elevations resembling those found in chickadees

maintained on limited and unpredictable food supply (14, 19). Corticosterone-implanted birds cached and consumed significantly more food and demonstrated more efficient cache recovery and enhanced spatial memory performance compared with placebo-implanted individuals (Fig. 4). Thus, contrary to prevailing assumptions, prolonged but moderate elevations of corticosterone actually enhanced spatial memory in food-caching mountain chickadees.

Long-term moderate corticosterone elevations and the hippocampus

The hippocampus has been implicated in spatial memory processing in both birds and mammals (29), and in food-caching birds, it has been shown that lesions of the hippocampal formation lead to impaired spatial memory performance (6, 30). It has been frequently suggested that any prolonged, chronic elevation in glucocorticoid stress hormones is damaging for both the hippocampus and its functions such as spatial memory (10, 11, 28).

Experiments with mountain chickadees demonstrated that moderately elevated corticosterone levels actually correlated with enhanced spatial memory performance in contrast with the expectation that any prolonged elevation of corticosterone should be detrimental for spatial memory. Furthermore, the volume of the hippocampal formation and the total number of the hippocampal neurons did not differ significantly between chickadees maintained on limited and unpredictable food and those on *ad libitum* food (Fig. 5). Thus, plasma corticosterone levels elevated due to long-term limited and unpredictable food supply had no significant effects on hippocampal anatomy in these birds.

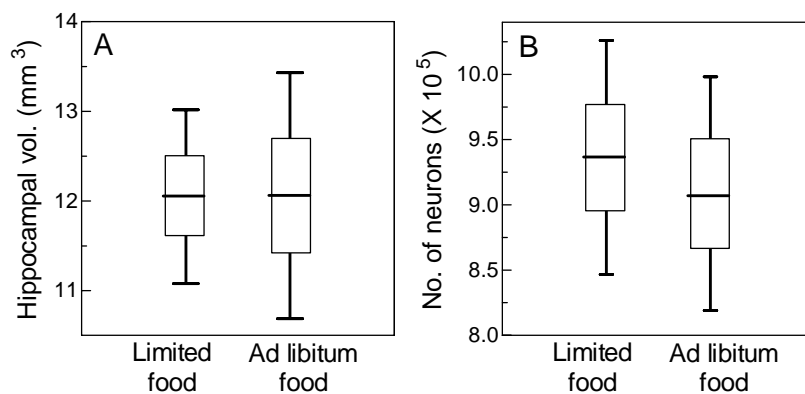


Fig. 5 Hippocampal volume (A) and the total number of hippocampal neurons (B) in mountain chickadees maintained on limited and unpredictable and on *ad libitum* food supply. Boxes represent SE and whiskers – 95% CI (data from 21).

Prolonged corticosterone elevation caused by implants enhanced spatial memory performance in mountain chickadees (14) but it did not have a significant effect on the hippocampal anatomy; hippocampal volume and the total number of hippocampal neurons did not differ significantly between corticosterone- and placebo- implanted individuals (Fig. 6).

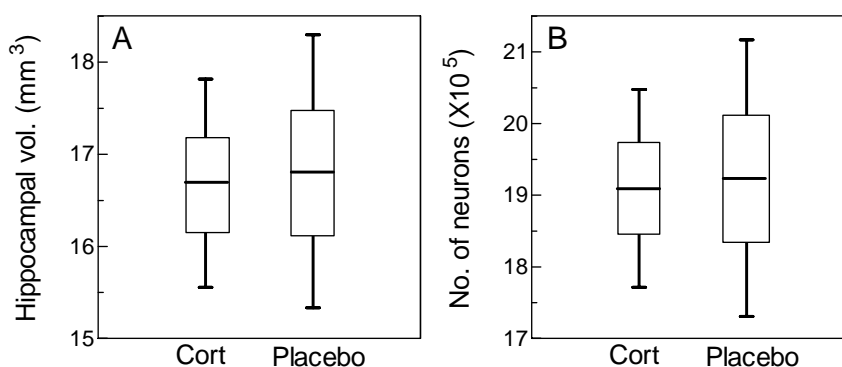


Fig. 6 Hippocampal volume (A) and the total number of hippocampal neurons (B) in corticosterone- and placebo-implanted mountain chickadees. Boxes represent SE and whiskers – 95 CI (data from 18).

Mammalian studies have suggested that chronic elevation in glucocorticoids might have a negative effect on the hippocampus by reducing hippocampal neurogenesis rates (5). However, chronic but moderate corticosterone elevation in mountain chickadees had no significant effect on hippocampal cell proliferation rates (Fig 7).

It is still possible that moderate chronic elevations of corticosterone have some negative effects on the avian hippocampus, but these effects did not seem to concern spatial memory since birds with moderately elevated corticosterone actually demonstrated enhanced spatial memory (14).

The experiment with limited and unpredictable feeding schedule and the experiment with corticosterone implants both resulted in spatial memory enhancements in mountain chickadees (14, 15). However, these changes in spatial memory were not associated with any detectable changes in the hippocampal anatomy or cell proliferation rates. This suggests that temporary (seasonal) changes in spatial memory are not necessarily mediated by changes in hippocampal volume or neuron numbers as it was suggested previously (34), but rather they could be mediated by changes in plasma corticosterone levels.

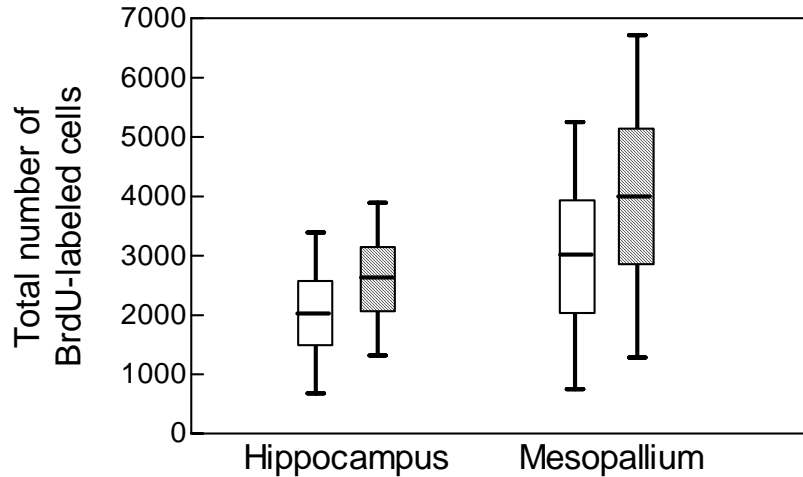


Fig. 7 Cell proliferation rates in the ventricular zone adjacent to either the hippocampus or to the mesopallium in corticosterone- (open bars) and placebo-implanted (hatched bars) mountain chickadees. Boxes represent SE and whiskers – 95% CI (data from 18).

Mechanism of corticosterone's effects on memory

There are several possible ways stress hormones can enhance memory formation. Elevated corticosterone could result in increased blood glucose levels and glucose has been implicated in enhancing memory function (4). Elevated corticosterone may also facilitate protein synthesis in the brain, which is also necessary for memory function (2, 24). Finally, there appears to be an inverted-U relationship between corticosterone levels and hippocampal neuron firing rates (3). Thus, moderate elevation in corticosterone levels might increase hippocampal neuron firing rate.

Conclusions

Chronic but moderate elevation of corticosterone appears to be an adaptive response to unpredictable environments. Food-caching birds wintering in high latitudes appear to respond to energetically demanding and variable environmental conditions by maintaining moderately elevated corticosterone levels, which would facilitate more intense foraging, fat accumulation, food caching and more efficient cache retrieval through enhanced spatial memory. Memory is an important mechanism used by food-caching birds for finding their caches and by enhancing spatial memory elevated corticosterone may increase these birds' survival probability during the winter (17). Such adaptive effects of prolonged but moderate elevations in corticosterone may be prevalent

but as yet are not well explored. The fact that corticosterone levels are reduced when conditions are favorable suggests that maintaining even moderately elevated corticosterone has its costs even though these costs do not seem to include previously assumed negative impacts on memory.

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