Current Zoology, 2021, 67(6), 631–638
doi: 10.1093/cz/zoab042
Advance Access Publication Date: 12 May 2021
Article

Article

Ecophysiology of egg rejection in hosts of avian brood parasites: new insights and perspectives

Francisco Ruiz-Raya *

Centro de Investigación Mariña, Universidade de Vigo, GEA, Vigo 36310, Spain

*Address correspondence to Francisco Ruiz-Raya. E-mail: francisco.ruiz.raya@uvigo.es

Handling editor: Canchao Yang (杨灿朝)

Received on 15 March 2021; accepted on 9 May 2021

Abstract

Egg rejection is the most effective and widespread defense used by host species to counteract the extreme fitness costs frequently imposed by obligate avian brood parasites. Yet, the proximate mechanisms underlying between- and within-individual variation in host responses remain poorly explored. Emerging evidence suggests that egg rejection is dependent on individual physiological states, and draws attention to the role of hormones as mediators of flexible antiparasitic responses. In this perspective article, I outline recent advances in our understanding of the proximate factors that mediate egg rejection. I also point out some areas where knowledge remains still lacking, especially those related to the development and maintenance of effective cognitive functions, the potential role of oxidative stress, immunological state, and developmental stressors. I propose new hypotheses that stimulate future research on behavioral host responses toward brood parasitism.

Key words: cognitive performance, condition-dependence, corticosterone, flexible responses, prolactin

Avian brood parasitism is an important selective force shaping a range of morphological and behavioral adaptations in some bird populations (Rothstein 1990). Obligate brood parasites lay their eggs in the nest of host species thereby exploiting the parental care that they provide to their offspring (RoldÄn and Soler 2011). The degree of virulence of brood parasitic species (i.e., the fitness costs that brood parasitism inflicts on hosts) is largely determined by the behavior of the parasitic chick, which often eliminates or outcompetes their foster siblings (Soler 2014; MoskÄt *et al.* 2017). In response, hosts have evolved successive lines of antiparasitic defenses that operate at all stages of the reproductive cycle (Feeney *et al.* 2014; Soler 2014, 2017a). The recognition and subsequent rejection of brood parasitic eggs is the most effective antiparasitic behavior (Feeney *et al.* 2014; Soler 2014), which can be achieved through the ejection of the parasitic egg or, alternatively, the abandonment of the complete clutch (Davies and Brooke 1989; Peer and Sealy 2004). Natural selection has favored the evolution of mimetic and polymorphic eggs in many brood parasitic species, which makes egg recognition harder for hosts (Brooke and Davies 1988; Yang *et al.* 2017). Egg-rejection decisions involve sensory stimuli associations within the nest, as well as flexible adjustments resulting from updating available information on the parasitism context (Ruiz-Raya and Soler 2020).

There is remarkable variation in egg rejection at all levels: individual, population, and species (Soler 2014). In some cases, this variation reflects differences in the extent of local adaptation across host populations as a result of dissimilar coevolutionary histories with brood parasites (Thompson 2005; Møller and Soler 2012); but also, absence of egg rejection may be the consequence of recent parasitism (evolutionary-lag hypothesis; Rothstein 1990). Sometimes, the acceptance of foreign eggs might be adaptive, presumably when rates (or costs) of brood parasitism are very low (evolutionary–equilibrium hypothesis; Rothstein 1990; KrÏger 2011). Finally, spatial and temporal differences in egg rejection can result from flexible adjustments in host responses according to the current risk of parasitism, previous experience, parasite retaliation, or social context (reviewed in Ruiz-Raya and Soler 2017). Egg rejection is the outcome of a decision-making process driven by 2 key components: host cognitive abilities and the influence of conditional factors (Stokke *et al.* 2005; Soler *et al.* 2012; Ruiz-Raya and Soler 2017). Co-evolutionary processes that

shape antiparasitic defenses have received considerable research attention over the last decades (reviewed in Feeney *et al.* 2014; Soler 2017a, 2017b). Egg-rejection experiments have revealed that hosts rely on discordance mechanisms (i.e., the rejection of the most dissimilar egg) and/or innate or learned templates of their own eggs' appearance (template-based mechanism) to recognize and reject foreign eggs (Manna *et al.* 2017). Studies on avian vision have provided detailed information about the specific visual cues and cognitive rules leading to egg rejection (e.g., Cassey *et al.* 2008; Spottiswoode and Stevens 2010; Stevens *et al.* 2013), and have shown the existence of marked sensory constraints in the cognitive decision rules used by some host species (Hanley *et al.* 2017).

However, comparatively few studies have explored the proximate causes behind between- and within-individual variability in egg rejection. Cognitive functions depend on individual physiological states, so cognitive performance is expected to be largely determined by the organisms' capacity to withstand environmental challenges (Buchanan *et al.* 2013; Maille and Schradin 2016; Cauchoix *et al.* 2020). It remains to be addressed whether the hosts' capacity to identify and reject parasitic eggs is dependent on their physiological state (e.g., hormone levels, energetic and immunological states, and oxidative status), or whether the development and maintenance of effective cognitive functions at adulthood can be constrained by adverse early-life conditions (Figure 1). Likewise, little is known about the physiological mechanisms that mediate the host propensity to egg rejection once the foreign egg has been identified. Hormones are prime candidates to mediate between- and within-individual variation in antiparasitic defenses (Abolins-Abols and Hauber 2018). Until recently, a handful of pioneering studies had investigated the role of hormones in host-brood parasite systems (Briskie *et al.* 1994; IbÄñez-àlamo *et al.* 2012; Mark and Rubenstein 2013; Hahn *et al.* 2017; Ruiz-Raya *et al.* 2018; Antonson *et al.* 2020; Scharf *et al.* 2021a, 2021b). Because, experimental evidence has confirmed that hormones indeed mediate host responses to brood parasitic eggs (Abolins-Abols and Hauber 2020a).

In this perspective article, I point out a number of physiological factors which could potentially impact host cognitive performance and explain individual variation in egg rejection. I provide new hypotheses to stimulate future research on condition-dependent responses to brood parasitic eggs. Finally, I discuss recent evidence on the endocrine mechanisms underlying egg rejection, with a special emphasis on prolactin, a pituitary hormone involved in the regulation of avian parental behavior.

Condition Dependence and Host Cognitive Performance

As in many other ecological contexts, effective cognitive functions are crucial in avian brood parasitic systems. Parasitic cowbirds (*Molothrus sp.*), for example, show sex-specific hippocampal specialization that allows females to map the location of host nests and form dynamic memory libraries on available parasitism opportunities (Scardamaglia *et al.* 2017; Sherry and Guigueno 2019). On their part, hosts can assess the local parasitism risk by combining personal and social information about the presence of brood parasites (for example, Gill and Sealy 2004; Welbergen and Davies 2012; Thorogood and Davies 2016; Tryjanowski *et al.* 2018). Rejecter hosts are able to acquire and integrate different informative signals that guide optimal rejection decisions, including the perceptual and cognitive process leading to egg recognition (Ruiz-Raya and Soler 2020). The host ability to identify and reject foreign eggs has evolved as the result of the strong selection pressures imposed by brood parasitism (Davies and Brooke 1989), and frequencies of potential *rejecters* and *acceptors* within host populations are known to have a strong genetic base (MartÕn-GÄlvez *et al.* 2006, 2007). Nonetheless, individual variation in cognitive performance can be caused by a number of noncognitive factors, such as experience or current motivational state (Rowe and Healy 2014).

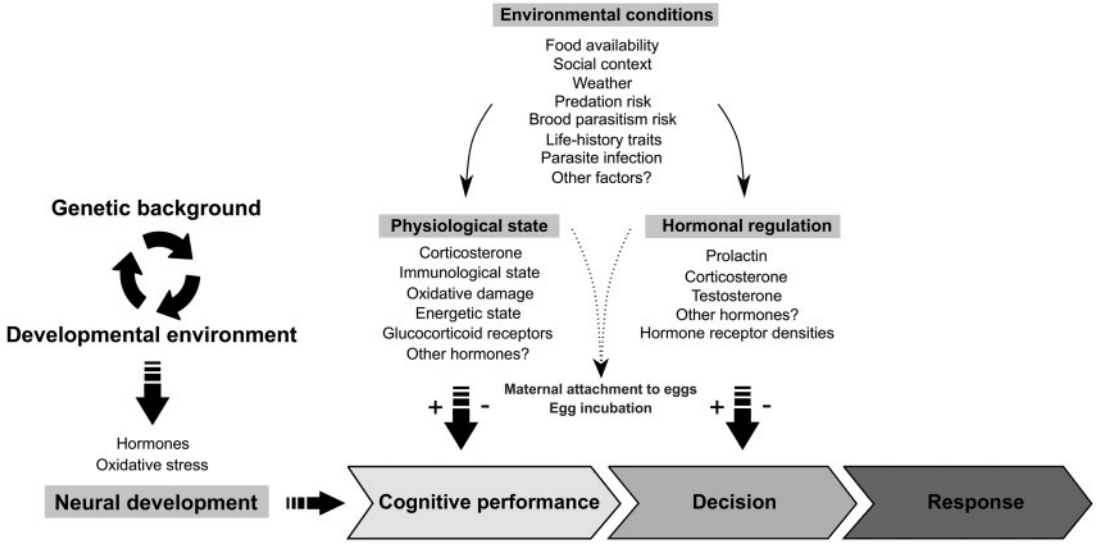

Figure 1. Potential physiological mechanisms mediating egg rejection. Egg rejection is a multi-stage process that requires effective perceptual and cognitive functions (cognitive performance), as well as the accurate integration of external cues of parasitism and the assessment of potential costs associated with the response (decision). Besides the genetic background, cognitive performance is determined by individual physiological states (cognitive flexibility; e.g., hormone levels, immunological state, and oxidative status) and developmental conditions (developmental cognitive plasticity). Main hormones involved in the regulation of parental care, such as prolactin, CORT, and testosterone, could also mediate changes in incubation and associative maternal behaviors in the nest, thereby impacting the probabilities of egg rejection.

Environmentally induced changes in physiology can either enhance or impair cognitive functions and explain much of the individual cognitive variation within bird populations (Buchanan *et al.* 2013; Maille and Schradin 2016). Beyond the genetic background, host cognitive abilities would therefore be expected to vary under different environmental contexts. The term *cognition* commonly refers to the acquisition, processing, and use of valuable information from the environment, this being essential for biologically relevant processes such as learning, memory, or decision making (Shettleworth 2010).Given the nonunitary nature of cognition, it is necessary a more precise delimitation of the specific cognitive ability that we are investigating (Rowe and Healy 2014). In egg-rejection studies, "host cognitive abilities" typically refer to the host capacity to recognize parasitic eggs so, accordingly, I will adopt this terminology throughout the present article to specifically refer to that cognitive task.

Despite the importance of effective egg-recognition abilities for rejecter species, the extent to which host cognitive performance depends on individual physiological states is unclear. There is evidence that some cognitive traits, such as problem-solving or learning, are condition-dependent, with individuals in better physiological states showing more effective cognitive abilities (BÆkony *et al.* 2014). In addition, the impact of early environmental conditions on the development of effective cognitive functions is another important factor that could explain individual differences in cognitive functions at adulthood (Buchanan *et al.* 2013). We still do not know whether environmental challenges can induce shifts in host cognitive performance, or whether cognitive functions underlying antiparasitic defenses are affected by developmental conditions in early life.

Environmental Stress, Physiological State, and Cognition

External (environmental) factors such as the social context or abiotic stressors, and the internal physiological state, are known to impact cognitive performance in vertebrates (Cauchoix *et al.* 2020). Brain tissues and neural processing are energetically expensive and require comparatively more energy than several other somatic tissues at rest (Laughlin 2001). Indeed, variations in body mass, or blood glucose levels, are associated with impaired cognitive abilities in birds, although the degree of impairment may depend on the intensity of food restriction and the energy status (Maille and Schradin 2016; Shaw 2017). Seasonal changes in food availability, body condition, or glucose levels might determine the outcome of the egg-rejection process, although this link may not be straightforward. The presence of nonmimetic eggs in the nest is known to impact the energy stores of adult hosts, presumably as a consequence of energy mobilization to cope with brood parasitism (Ruiz-Raya *et al.* 2018). In some species, egg rejection probability appears to be negatively related to body mass at an intraspecific level (Abolins-Abols and Hauber 2020b), yet the effects of seasonal changes in body condition on host cognitive performance are still unclear.

Hormones could mediate the effects of environmental challenges on cognition and lead to reversible changes in host performance. Catecholamine and glucocorticoid responses to stress are known to influence cognitive functions, although their effects depend on the intensity and duration of stressors (McEwen and Sapolsky 1995; Maille and Schradin 2016). Moderate and short-term elevations in corticosteroid levels enhance cognition, whereas greater and sustained increases in circulating corticosteroids can lead to cognitive impairment (Pravosudov 2003; Lupien *et al.* 2009). Individual differences in baseline glucocorticoids, or changes in glucocorticoid levels in response to environmental challenges, have been hypothesized to impact the host's ability to recognize and reject parasitic eggs. In American robins, *Turdus migratorius*, an occasional host of the brown-headed cowbird *Molothrus ater*, the probability of egg rejection has been shown to be negatively related to plasma corticosterone (CORT) levels (Abolins-Abols and Hauber 2020b). In another experimental study, the authors found that the suppression of CORT synthesis through mitotane injections increased the probability of egg acceptance by female robins (Abolins-Abols and Hauber 2020a). These results strongly suggest that glucocorticoids mediate behavioral responses to parasitic eggs and bring new insights into the endocrine regulation of egg rejection. Future studies should determine whether variations in CORT levels impact host cognitive performance or, instead, modify maternal behaviors in the nest (e.g., maternal attachment to eggs; Figure 1).

Other aspects of host physiology, such as oxidative status, could mediate life-history trade-offs linked to individual cognitive performance. The relative abundance of pro-oxidant and antioxidant agents occurring in cells determines the individual reproductive potential, gradual deterioration of bodyline functions, and lifespan (Monaghan *et al.* 2009). Specifically, prolonged exposure to oxidative stress is expected to lead to brain damage and cognitive impairment (Liu *et al.* 2003; DrÎge and Schipper 2007). In birds, plasma levels of enzymatic antioxidant are positively associated with enhanced cognitive functions (BÆkony *et al.* 2014), whereas the increased production of plasma lipid peroxidation markers (malonaldehyde, MDA), and the simultaneous decrease in antioxidants (superoxide dismutase, SOD and glutathione peroxidase, GPX), are linked to cognitive impairment (Padurariu *et al.* 2010). One might simplistically predict that those individuals showing evidence of accumulated oxidative damage (e.g., increased plasma MDA levels), or lower antioxidant levels, will show poorer sensory–cognitive abilities to recognize and reject parasitic eggs. Likely, the study of different components of oxidative stress will allow us to obtain a broader view of individual oxidative status. Among the most feasible measurements are enzymatic and nonenzymatic antioxidant defenses, total antioxidant capacity, and measurements of oxidative damage to proteins, lipids, and DNA (Monaghan *et al.* 2009).

Oxidative stress has been suggested to underly life-history trade-offs associated with reproductive costs (Monaghan *et al.* 2009; Metcalfe and Monaghan 2013). Further experimental investigation is needed to establish whether there is any link between parental investment and host cognitive performance. Evolutionary cost–benefit theory predicts that hosts investing more in reproduction will be more likely to reject brood parasitic eggs (the "maternal investment" hypothesis; Hauber *et al.* 2020). However, if greater reproductive effort does lead to increased oxidative damage to the soma (and impaired brain functions), then hosts investing more in their clutch (e.g., larger eggs and broods, earlier onset of laying, and post-hatching investment) might exhibit impaired cognitive abilities. Correlational evidence suggests that hosts with smaller clutches are more likely to reject brood parasitic eggs (Abolins-Abols and Hauber 2020b), although further studies are needed to establish a causal link between parental effort and host cognitive performance.

Similarly, given the link between aging, oxidative stress, and cognitive decline (Golden *et al.* 2002; DrÎge and Schipper 2007), it

could be predicted the existence of age-dependent responses to brood parasitism, with old individuals showing impaired cognitive performance. Current evidence, however, suggests that egg-rejection abilities do not decrease over the life. In the great-spotted cuckoo *Clamator glandarius*—magpie *Pica pica* system, longer-lived magpies are more likely to reject cuckoo eggs, so brood parasites are expected to benefit from exploiting young and naÝve individuals (MartÕnez *et al.* 2020). Long-lived hosts might show reduced cumulative oxidative damage, or physiological mechanisms to resist oxidative stress. As the development and maintenance of cognitive skills are costly, it should be only favored when individuals obtain fitness benefits from effective cognitive abilities (Morand-Ferron *et al.* 2016). Natural selection should select for physiological mechanisms protecting essential cognitive functions against the detrimental effects of seasonal environmental challenges (cognitive resilience; Buchanan *et al.* 2013). Given the high fitness costs linked to brood parasitism, resilience mechanisms would reduce the brain susceptibility to stress and allow rejecter species to maintain an effective cognitive performance. These mechanisms might involve the modulation of glucocorticoid receptor densities, or sensitivity, protecting essential cognitive abilities against changes in glucocorticoid levels. Also, the detrimental effects of oxidative stress could be buffered through the modulation of circulating antioxidants (Buchanan *et al.* 2013).

Future studies should explore potential trade-offs between cognitive performance and the immune system in the context of avian brood parasitism. Pathogens have a negative impact on cognitive functions in vertebrates, including humans (Jukes *et al.* 2002; Binning *et al.* 2018), and parasite infection is known to impact cognitive performance in birds (Ducatez *et al.* 2020). Brood parasitism increases bacterial load in parasitized nests (Soler *et al.* 2011); however, whether parasite infection in adult hosts impacts their cognitive performance is unknown. Equally, recent research has highlighted the role of the gut microbiome as a potential driver of individual cognitive variation in natural populations. Avian gut microbiota is affected by a number of intrinsic (e.g., age, sex, diet, and behavior) and extrinsic factors (e.g., environment and resources; Grond *et al.* 2018), and the gut–brain axis seems to play a key role in brain functions and the maintenance of effective cognitive abilities (Davidson *et al.* 2018). Gut microbiota has been characterized in different brood parasite–hosts systems (Ruiz-RodrÕguez *et al.* 2009; Lee *et al.* 2020; Schmiedova *et al.* 2020), but the link between gut microbiome and host cognitive performance at adulthood has not yet been explored. Experimental manipulations of gut microbial communities at both perinatal environments and adulthood would likely help to disentangle the potential link between host performance and gut microbiota (Davidson *et al.* 2018).

Developmental Conditions and Cognitive Performance

Early-life events induce anatomical, behavioral, and physiological changes in developmental trajectories (West-Eberhard 2003). Environmental conditions experienced during early development shape individual phenotypes and have long-lasting effects on cognitive functions (Buchanan *et al.* 2013). Early-life stress has deleterious effects on a number of cognition-dependent traits in birds, such as spatial memory or vocal learning (Buchanan *et al.* 2003; Spencer *et al.* 2003; Pravosudov 2009). Nutritional deficits and chronic exposure to glucocorticoids during postnatal development impair cognitive performance at adulthood (Kitaysky *et al.* 2003; Pravosudov *et al.* 2005; Lucassen *et al.* 2013). In some brood parasitic systems, host nestlings are exposed to important nutritional and physiological stressors. Nonevictor parasitic young are preferentially fed by their foster parents (Soler *et al.* 1995; Lorenzana and Sealy 1999; Soler 2017b) and outcompete host nestlings (Soler 2017b), not only for quantity of food, but also for high-quality food, thereby imposing nutritional restrictions on host offspring (Ladin *et al.* 2015). Host nestlings may respond by increasing the intensity of begging signals to compete with their parasitic nestmates (Rivers *et al.* 2010), which could lead to immunological (Moreno-Rueda 2010) and oxidative costs (Noguera *et al.* 2010). Interestingly, IbÄñez-àlamo *et al.* (2012) found that magpie nestlings reared together with great-spotted cuckoos had higher CORT levels than magpies from unparasitized nests, which indicates that sharing the nest with parasitic chicks is an important physiological stressor for developing hosts (but see Scharf *et al.* 2021b).

Brood parasitism is associated with faster growth rate and shorter nestling periods in hosts, these effects being more pronounced in host species showing higher sibling competition (Remes 2006). Faster growth rates may cause the loss of cognitive abilities in adulthood (Fisher *et al.* 2006), so the accelerated nestling growth might impact the host's ability to respond against brood parasitism in adulthood, especially in small-sized hosts in which sibling competition is more intense. Alternatively, it could be predicted the existence of resilience mechanisms protecting hosts from the negative effects of early-life stressors. Brood parasitism is known to result in carry-over effects on future reproductive effort in adult hosts (Mark and Rubenstein 2013); however, whether sharing the nest with parasitic chicks has long-term effects on host cognitive performance is still unknown.

Beyond Egg Recognition: Endocrine Regulation of Flexible Host Responses

The outcome of the egg-rejection process is largely determined by intrinsic sensory and perceptual abilities, but egg rejection is likewise conditioned by a number of environmental and life-history factors, such as the risk of parasitism or parasite retaliation, the moment of the breeding season, or previous experience (reviewed in Ruiz-Raya and Soler 2017). This means that egg rejection does not only depend on the host's ability to recognize foreign eggs, but also on its propensity to reject them. Several hypotheses have been proposed to explain how hormones mediate the host propensity to either reject or accept foreign eggs, paving the way for clear predictions about proximate factors underlying flexible changes in rejection responses. Abolins-Abols and Hauber (2018) provided a comprehensive overview on the endocrine mechanisms potentially underlying antiparasitic behaviors at different stages of the breeding cycle. The authors argue that the propensity to accept or reject any egg in the nest is mediated by major hormones involved in the regulation of avian parental behavior. For instance, endocrine pathways involved in the suppression of maternal behavior might regulate the ejection of parasitic eggs or nest desertion decisions. Whereas empirical evidence on the endocrine regulation of egg rejection is still scarce, recent experimental studies have provided strong support for the role of certain hormones (e.g., prolactin and CORT) as mediators of host responses to brood parasitism. Below, I outline recent advances and future avenues in understanding the hormonal bases of egg rejection.

Prolactin is a pituitary hormone that mediates major aspects of avian parental care, including ultimate decisions such as the

abandonment of eggs and chicks (Angelier and Chastel 2009). Plasma prolactin levels are positively related to the initiation and maintenance of associative parental behavior in birds (e.g., egg incubation and post-hatching parental care), whereas decreasing prolactin concentrations are often linked to breeding failure (Angelier and Chastel 2009; Angelier *et al.* 2016; Smiley 2019). Prolactin is thought to mediate those antiparasitic defenses that entail the suppression of affiliative parental behaviors, such as the ejection of foreign eggs and the complete abandonment of parasitized clutches (Abolins-Abols and Hauber 2018; Ruiz-Raya and Soler 2020). Recent studies have revealed that the experimental reduction of plasma prolactin concentrations through bromocriptine implants increases the probabilities of egg rejection in Eurasian blackbirds (*Turdus merula*; Ruiz-Raya et al. submitted for publication). Notably, bromocriptine-treated blackbirds showed higher ejection rates and faster rejection decisions (without incurring in recognition errors) in response to mimetic model eggs. Experimental evidence confirms that decreasing prolactin levels facilitate egg-ejection decisions, yet future research should investigate whether prolactin can somehow impact cognitive performance in other host species.

Circulating prolactin levels often decrease in response to environmental stressors (Angelier and Chastel 2009; Angelier *et al.* 2016). This prolactin response to stress may help to disentangle the proximate mechanisms mediating flexible responses to parasitic eggs. Cues of brood parasitism, such as the presence of adult parasites or social information on parasitism risk, might lead to changes in plasma prolactin levels and thus facilitate egg-rejection decisions. Whereas the presence of nonmimetic eggs in the nest does not seem to modify prolactin levels in adult hosts, experimentally parasitized individuals exhibit a more robust prolactin response to standardized stressors (Ruiz-Raya *et al.* 2018). This suggests that prolactin response may be more complex than expected and require multiple cues of parasitism (e.g., a parasitic egg and the presence of the adult parasite). Experimental studies assessing the host's prolactin response to variable risk of parasitism will be essential to understand the role of endocrine flexibility in mediating antiparasitic defenses.

Prolactin regulation of antiparasitic defenses may be especially important in host species that use nest abandonment as the main rejection mechanism, as are the cases of many brown-headed cowbird hosts (Hosoi and Rothstein 2000). In such cases, individual differences in circulating prolactin could determine the host propensity to abandon the nests. In medium-sized hosts, the experimental reduction of plasma prolactin concentrations does not affect the probability of nest abandonment in response to experimental parasitism (Ruiz-Raya et al. submitted for publication). However, it is noteworthy that medium-sized ejectors might not use nest desertion as a genuine response to brood parasitism (Soler *et al.* 2015; but see Hosoi and Rothstein 2000). The role of prolactin in mediating nest desertion responses should be further explored in small-sized hosts which are not able to reject parasitic eggs by grasping or puncturing them. In addition, it should be noted that the adaptive value of nest desertion is likely determined by life-history traits. As nest abandonment would be adaptive only when the value of current reproduction is low (e.g., lower clutch sizes; Servedio and Hauber 2006), prolactin might mediate optimal rejection decisions according to the fitness payoffs of alternative host responses. Prolactin decreases in response to environmental stressors can be downregulated to maintain parental care when current reproduction has important fitness value (Angelier and Chastel 2009; Angelier *et al.* 2016).

Other hormones, such as testosterone and CORT, which both play key roles as mediators of parental behavior in bird species (Schoech *et al.* 1998; BÆkony *et al.* 2009), could likewise impact the host propensity to egg rejection (Figure 1). CORT might directly affect host's cognitive performance (see above), but also impact the host behavior once the parasitic egg has been recognized. CORT responsiveness to environmental factors has been suggested to be an important mechanism mediating flexible host responses to brood parasitism (Abolins-Abols and Hauber 2018). For example, raising CORT levels in response to brood parasitism (or high risk of brood parasitism) could suppress affiliative parental behavior and facilitate rejection decisions. As seen above, decreasing CORT levels are known to reduce egg-rejection responses in American robins (Abolins-Abols and Hauber 2020a). Experimental parasitism causes an increase in CORT levels in host species with fine-tuned recognition abilities (Ruiz-Raya *et al.* 2018); however, accepter species show unaffected plasma CORT levels in response to foreign eggs (Scharf *et al.* 2021a). These results indicate that changes in plasma CORT elicited by parasitic eggs orchestrate effective responses to brood parasitism, a process that will likely depend on egg mimicry and host recognition abilities. Finally, given that prolactin can act sequentially or interact with other hormones such as CORT (Angelier *et al.* 2016), further studies should consider that the effect of CORT might depend on the circulating levels of prolactin.

Concluding Remarks

The host abilities to recognize and reject brood parasitic eggs have been widely explored in different brood parasitic systems, which have brought us closer to understanding the co-evolutionary forces that shape avian brood parasite–host interactions. Despite this, we still lack knowledge about the proximate mechanisms underlying individual variation in egg rejection. In this article, I propose that host cognitive performance and rejection decisions are dependent on individual physiological conditions (e.g., hormone levels, oxidative status, immunological, and energetic state). Individual differences in cognitive performance would be determined not only by genetic inheritance, but other factors, such as developmental history (cognitive plasticity), social context, or the effects of environmental stressors, should also be considered (Boogert *et al.* 2018; Cauchoix *et al.* 2020). Future studies should explore how changes in host physiology across early-life and adult environments affect cognitive performance in egg-rejection experiments. Understanding how physiology determines individual variation in host performance will likely be challenging because sensory, perception, and cognitive performance cannot be directly observed. Egg-rejection rates alone will not allow to separate the perceptual and conditional components of egg rejection, so future research will benefit from the use of both behavioral (e.g., egg-touching behavior) and physiological (e.g., hormone variation) proxies of egg recognition to assess cognitive performance separately from host responses (Ruiz-Raya and Soler 2020).

Even though individual differences in cognition are well documented among vertebrate taxa (Thornton and Lukas 2012), the extent to which these variations determine the reproductive fitness in wild populations remains challenging (Morand-Ferron *et al.* 2016). In avian brood parasitic systems, fine-tuned cognitive abilities (e.g., strong egg-recognition abilities) are essential to avoid the frequently high fitness costs inflicted by brood parasitism, so physiological mechanisms favoring cognitive resilience would be expected to be found in host species. These resilience mechanisms might operate by modulating tissue sensitivity to stress (e.g., glucocorticoids receptor

density), or protecting the brain from the detrimental effects of oxidative damage (e.g., antioxidant defenses).

The evidence reviewed here strongly suggests that egg rejection is mediated by endocrine pathways involved in the regulation of parental behavior, yet additional research is needed to unravel whether the endocrine regulation of host responses is associated with variations in cognitive performance or changes in associative maternal behaviors, as seems to be the case with prolactin. Future studies should explore whether different hormones (e.g., prolactin, CORT, and testosterone) interact to mediate egg-rejection behaviors. Finally, besides changes in plasma hormone concentration, the endocrine regulation of egg rejection will likely involve different components of endocrine networks such hormone receptor densities or carrier proteins (Breuner *et al*. 2012; Rosvall 2013). Studying the physiological mechanisms mediating egg-rejection behavior will bring new insights into the causes of individual variation in antiparasitic host defenses and shed light on the proximate factors underlying flexible host responses to brood parasitism.

Acknowledgments

I thank Canchao Yang for the opportunity to contribute to this special column. I also thank Manuel Soler for his constructive comments on an earlier version of this manuscript.

Funding

FRR was supported by the Spanish MINECO's Juan de la Cierva-FormaciÆn programme (grant FJC2018-037157-I).

References

Abolins-Abols M, Hauber ME, 2018. Host defences against avian brood parasitism: an endocrine perspective. *Proc R Soc B Biol Sci* **285**:20180980.

Abolins-Abols M, Hauber ME, 2020a. Endocrine regulation of egg rejection in an avian brood parasite host. *Biol Lett* **16**:20200225.

Abolins-Abols M, Hauber ME, 2020b. Proximate predictors of variation in egg rejection behavior by hosts of avian brood parasites. *J Comp Psychol* **134**:412–422.

Angelier F, Chastel O, 2009. Stress, prolactin and parental investment in birds: a review. *Gen Comp Endocrinol* **163**:142–148.

Angelier F, Wingfield JC, Tartu S, Chastel O, 2016. Does prolactin mediate parental and life-history decisions in response to environmental conditions in birds? A review. *Horm Behav* **77**:18–29.

Antonson ND, Hauber ME, Mommer BC, Hoover JF, Schelsky WM, 2020. Physiological responses of host parents to rearing an avian brood parasite: an experimental study. *Horm Behav* **125**:104812.

Binning SA, Roche DG, Grutter AS, Colosio S, Sun D et al., 2018. Cleaner wrasse indirectly affect the cognitive performance of a damselfish through ectoparasite removal. *Proc R Soc B Biol Sci* **285**:20172447.

BÆkony V, Lendvai âZ, VÄgÄsi CI, Pătraş L, Pap PL et al., 2014. Necessity or capacity? Physiological state predicts problem-solving performance in house sparrows. *Behav Ecol* **25**:124–135.

BÆkony V, Lendvai AZ, Liker A, Angelier F, Wingfield JC et al., 2009. Stress response and the value of reproduction: are birds prudent parents. *Am Nat* **173**:589–598.

Boogert NJ, Madden JR, Morand-Ferron J, Thornton A, 2018. Measuring and understanding individual differences in cognition. *Philos Trans R Soc B Biol Sci* **373**:20170280.

Breuner CW, Delehanty B, Boonstra R, 2012. Evaluating stress in natural populations of vertebrates: total CORT is not good enough. *Funct Ecol* **27**:24–36.

Briskie JV, Naugler CT, Leech SM, 1994. Begging intensity of nestling birds varies with sibling relatedness. *Proc R Soc B Biol Sci* **258**:73–78.

Brooke MDL, Davies NB, 1988. Egg mimicry by cuckoos *Cuculus canorus* in relation to discrimination by hosts. *Nature* **335**:630–632.

Buchanan KL, Grindstaff JL, Pravosudov VV, 2013. Condition dependence, developmental plasticity, and cognition: implications for ecology and evolution. *Trends Ecol Evol* **28**:290–296.

Buchanan KL, Spencer KA, Goldsmith AR, Catchpole CK, 2003. Song as an honest signal of past developmental stress in the European starling (*Sturnus vulgaris*). *Proc R Soc B Biol Sci* **270**:1149–1156.

Cassey P, Honza M, Grim T, Hauber ME, 2008. The modelling of avian visual perception predicts behavioural rejection responses to foreign egg colours. *Biol Lett* **4**:515–517.

Cauchoix M, Chaine AS, Barragan-Jason G, 2020. Cognition in context: plasticity in cognitive performance in response to ongoing environmental variables. *Front Ecol Evol* **8**:1–8.

Davidson GL, Cooke AC, Johnson CN, Quinn JL, 2018. The gut microbiome as a driver of individual variation in cognition and functional behaviour. *Philos Trans R Soc B Biol Sci* **373**:20170286.

Davies NB, Brooke MDL, 1989. An experimental study of co-evolution between the cuckoo *Cuculus canorus* and its hosts. I. Host egg discrimination. *J Anim Ecol* **58**:207–224.

DrÎge W, Schipper HM, 2007. Oxidative stress and aberrant signaling in aging and cognitive decline. *Aging Cell* **6**:361–370.

Ducatez S, Lefebvre L, Sayol F, Audet JN, Sol D, 2020. Host cognition and parasitism in birds: a review of the main mechanisms. *Front Ecol Evol* **8**:1–15.

Feeney WE, Welbergen JA, Langmore NE, 2014. Advances in the study of coevolution between avian brood parasites and their hosts. *Annu Rev Ecol Evol Syst* **45**:227–246.

Fisher MO, Nager RG, Monaghan P, 2006. Compensatory growth impairs adult cognitive performance. *PLoS Biol* **4**:1462–1466.

Gill SA, Sealy SG, 2004. Functional reference in an alarm signal given during nest defence: seet calls of yellow warblers denote brood-parasitic brown--headed cowbirds. *Behav Ecol Sociobiol* **56**:71–80.

Golden TR, Hinerfeld DA, Melov S, 2002. Oxidative stress and aging. *Aging Cell* **1**:323–338.

Grond K, Sandercock BK, Jumpponen A, Zeglin LH, 2018. The avian gut microbiota: community, physiology and function in wild birds. *J Avian Biol* **49**:1–19.

Hahn DC, Wingfield JC, Fox DM, Walker BG, Thomley JE, 2017. Maternal androgens in avian brood parasites and their hosts: responses to parasitism and competition? *Gen Comp Endocrinol* **240**:143–152.

Hanley D, Grim T, Igic B, Samaš P, LÆpez AV et al., 2017. Egg discrimination along a gradient of natural variation in eggshell coloration. *Proc R Soc Biol Sci* **284**:20162592.

Hauber ME, Abolins-Abols M, Kim CR, Paitz RT, 2020. Inter-individual variation in anti-parasitic egg rejection behavior: a test of the maternal investment hypothesis. *Integr Org Biol* **2**:obaa014.

Hosoi S, Rothstein SI, 2000. Nest desertion and cowbird parasitism: evidence for evolved responses and evolutionary lag. *Anim Behav* **59**:823–840.

IbÄñez-àlamo JD, De Neve L, RoldÄn M, RodrÕguez-Ruiz J, TrouvÅ C et al., 2012. CORTlevels in host and parasite nestlings: is brood parasitism a hormonal stressor. *Horm Behav* **61**:590–597.

Jukes MCH, Nokes CA, Alcock KJ, Lambo JK, Kihamia C et al., 2002. Heavy schistosomiasis associated with poor short-term memory and slower reaction times in Tanzanian schoolchildren: partnership for child development. *Trop Med Int Heal* **7**:104–117.

Kitaysky AS, Kitaiskaia EV, Piatt JF, Wingfield JC, 2003. Benefits and costs of increased levels of CORTin seabird chicks. *Horm Behav* **43**:140–149.

KrÎger O, 2011. Brood parasitism selects for no defence in a cuckoo host. *Proc Biol Sci* **278**:2777–2783.

Ladin ZS, D'Amico V, Jaisi DP, Shriver WG, 2015. Is brood parasitism related to host nestling diet and nutrition? *Auk* **132**:717–734.

Laughlin SB, 2001. Energy as a constraint on the coding and processing of sensory information. *Curr Opin Neurobiol* **11**:475–480.

Lee CY, Peralta-SÄnchez JM, MartÕnez-Bueno M, Møller AP, Rabelo-Ruiz M et al., 2020. The gut microbiota of brood parasite and host nestlings

reared within the same environment: disentangling genetic and environmental effects. *ISME J* **14**:2691–2702.

Liu R, Liu IY, Bi X, Thompson RF, Doctrow SR et al., 2003. Reversal of age-related learning deficits and brain oxidative stress in mice with superoxide dismutase/catalase mimetics. *Proc Natl Acad Sci USA* **100**:8526–8531.

Lorenzana JC, Sealy SG, 1999. A meta-analysis of the impact of parasitism by the Brown-headed Cowbird on its hosts. *Stud Avian Biol* **18**:241–253.

Lucassen PJ, Naninck EFG, van Goudoever JB, Fitzsimons C, Joels M et al., 2013. Perinatal programming of adult hippocampal structure and function; Emerging roles of stress, nutrition and epigenetics. *Trends Neurosci* **36**:621–631.

Lupien SJ, McEwen BS, Gunnar MR, Heim C, 2009. Effects of stress throughout the lifespan on the brain, behaviour and cognition. *Nat Rev Neurosci* **10**:434–445.

Maille A, Schradin C, 2016. Ecophysiology of cognition: how do environmentally induced changes in physiology affect cognitive performance? *Biol Rev* **1102**:1101–1112.

Manna T, MoskÄt C, Hauber ME, 2017. Cognitive decision rules for egg rejection. In: Soler M, edtitor. *Avian Brood Parasitism - Behaviour, Ecology, Evolution and Coevolution*. Berlin/Heidelberg, Germany: Springer. 437–48.

Mark MM, Rubenstein DR, 2013. Physiological costs and carry-over effects of avian interspecific brood parasitism influence reproductive tradeoffs. *Horm Behav* **63**:717–722.

MartÕn-GÄlvez D, Soler JJ, MartÕnez JG, Krupa AP, Richard M et al., 2006. A quantitative trait locus for recognition of foreign eggs in the host of a brood parasite. *J Evol Biol* **19**:543–550.

MartÕn-GÄlvez D, Soler JJ, MartÕnez JG, Krupa AP, Soler M et al., 2007. Cuckoo parasitism and productivity in different magpie subpopulations predict frequencies of the 457bp allele: a mosaic of coevolution at a small geographic scale. *Evolution (N Y)* **61**:2340–2348.

MartÕnez JG, Molina-Morales M, Precioso M, AvilÅs JM, 2020. Age-related brood parasitism and egg rejection in magpie hosts. *Am Nat* **195**:876–885.

McEwen BS, Sapolsky RM, 1995. Stress and cognitive function. *Curr Opin Neurobiol* **5**:205–216.

Metcalfe NB, Monaghan P, 2013. Does reproduction cause oxidative stress? An open question. *Trends Ecol Evol* **28**:347–350.

Møller AP, Soler JJ, 2012. A coevolutionary framework based on temporal and spatial ecology of host-parasite interactions: a missing link in studies of brood parasitism. *Chinese Birds* **3**:259–273.

Monaghan P, Metcalfe NB, Torres R, 2009. Oxidative stress as a mediator of life history trade-offs: mechanisms, measurements and interpretation. *Ecol Lett* **12**:75–92.

Morand-Ferron J, Cole EF, Quinn JL, 2016. Studying the evolutionary ecology of cognition in the wild: a review of practical and conceptual challenges. *Biol Rev* **91**:367–389.

Moreno-Rueda G, 2010. An immunological cost of begging in house sparrow nestlings. *Proc R Soc B Biol Sci* **277**:2083–2088.

MoskÄt C, Hauber ME, Louder MIM, 2017. The evolution of nest sharing and nest mate killing strategies in brood parasites. In: Soler M, editor. *Avian Brood Parasitism Behaviour, Ecology, Evolution and Coevolution*. Cham, Switzerland: Springer. 475–92.

Noguera JC, Morales J, PÅrez C, Velando A, 2010. On the oxidative cost of begging: antioxidants enhance vocalizations in gull chicks. *Behav Ecol* **21**:479–484.

Padurariu M, Ciobica A, Hritcu L, Stoica B, Bild W et al., 2010. Changes of some oxidative stress markers in the serum of patients with mild cognitive impairment and Alzheimer's disease. *Neurosci Lett* **469**:6–10.

Peer BD, Sealy SG, 2004. Correlates of egg rejection in hosts of the brown--headed cowbird. *Condor* **106**:580–599.

Pravosudov VV, 2003. Long-term moderate elevation of CORTfacilitates avian food-caching behaviour and enhances spatial memory. *Proc R Soc B Biol Sci* **270**:2599–2604.

Pravosudov VV, 2009. Development of spatial memory and the hippocampus under nutritional stress: adaptive priorities or developmental constraints in brain development? In: Dukas R, Ratcliffe JM, editors. *Cognitive Ecology II*. Chicago (IL): University of Chicago Press. 88–110.

Pravosudov VV, Lavenex P, Omanska A, 2005. Nutritional deficits during early development affect hippocampal structure and spatial memory later in life. *Behav Neurosci* **119**:1368–1374.

Remes V, 2006. Growth strategies of passerine birds are related to brood parasitism by the brown-headed cowbird *Molothrus Ater*. *Evolution (N Y)* **60**:1692.

Rivers JW, Loughin TM, Rothstein SI, 2010. Brown-headed cowbird nestlings influence nestmate begging, but not parental feeding, in hosts of three distinct sizes. *Anim Behav* **79**:107–116.

RoldÄn M, Soler M, 2011. Parental-care parasitism: how do unrelated offspring attain acceptance by foster parents? *Behav Ecol* **22**:679–691.

Rosvall KA, 2013. Proximate perspectives on the evolution of female aggression: good for the gander, good for the goose? *Philos Trans R Soc B* **368**:20130083.

Rothstein SI, 1990. A model system for coevolution: avian brood parasitism. *Annu Rev Ecol Syst* **21**:481–508.

Rowe C, Healy SD, 2014. Measuring variation in cognition. *Behav Ecol* **25**:1287–1292.

Ruiz-Raya F, Soler M. 2017. Phenotypic plasticity in egg rejection: evidence and evolutionary consequences. In: Soler M, editor. *Avian Brood Parasitism - Behaviour, Ecology, Evolution and Coevolution*. Berlin/Heidelberg, Germany: Springer. 449–71.

Ruiz-Raya F, Soler M, 2020. Signal detection and optimal acceptance thresholds in avian brood parasite–host systems: implications for egg rejection. *Philos Trans R Soc B* **375**:1–9.

Ruiz-Raya F, Soler M, Abaurrea T, Chastel O, Roncalli G et al., 2018. Hormonal responses to non-mimetic eggs: is brood parasitism a physiological stressor during incubation? *Behav Ecol Sociobiol* **72**:1–11.

Ruiz-RodrÕguez M, Lucas FS, Heeb P, Soler JJ, 2009. Differences in intestinal microbiota between avian brood parasites and their hosts. *Biol J Linn Soc* **96**:406–414.

Scardamaglia RC, Fiorini VD, Kacelnik A, Reboreda J, 2017. Planning host exploitation through prospecting visits by parasitic cowbirds. *Behav Ecol Sociobiol* **71**:23.

Scharf HM, Abolins-Abols M, Stenstrom K, Tolman DT, Schelsky WM et al., 2021a. Exposure to a mimetic or non-mimetic model avian brood parasite egg does not produce differential glucocorticoid responses in an egg-accepter host species. *Gen Comp Endocrinol* **304**:113723.

Scharf HM, Hauber ME, Mommer BC, Hoover JP, Schelsky WM, 2021b. The effect of avian brood parasitism on physiological responses of host nestlings. *Oecologia* **1**:3.

Schmiedova L, Kreisinger J, Požgayova M, Honza M, Martin JF et al., 2020. Gut microbiota in a host-brood parasite system: insights from common cuckoos raised by two warbler species. *FEMS Microbiol Ecol* **96**:1–10.

Schoech SJ, Ketterson ED, Nolan V, Sharp PJ, Buntin JD et al., 1998. The effect of exogenous testosterone on parental behavior, plasma prolactin, and prolactin binding sites in dark-eyed juncos. *Horm Behav* **34**:1–10.

Servedio MR, Hauber ME, 2006. To eject or to abandon? Life history traits of hosts and parasites interact to influence the fitness payoffs of alternative anti-parasite strategies. *J Evol Biol* **19**:1585–1594.

Shaw RC, 2017. Testing cognition in the wild: factors affecting performance and individual consistency in two measures of avian cognition. *Behav Processes* **134**:31–36.

Sherry DF, Guigueno MF, 2019. Cognition and the brain of brood parasitic cowbirds. *Integr Zool* **14**:145–157.

Shettleworth SJ, 2010. *Cognition, Evolution, and Behavior*. Oxford: Oxford University Press.

Smiley KO, 2019. Prolactin and avian parental care: new insights and unanswered questions. *Horm Behav* **111**:114–130.

Soler JJ, Peralta-SÄnchez JM, MartÕnez-Bueno M, MartÕn-Vivald M, MartÕn-GÄlvez D et al., 2011. Brood parasitism is associated with increased bacterial contamination of host eggs: bacterial loads of host and parasitic eggs. *Biol J Linn Soc* **103**:836–848.

Soler M, 2014. Long-term coevolution between avian brood parasites and their hosts. *Biol Rev* **89**:688–704.

Soler M, 2017a. Avian brood parasitism - behaviour. In: Soler M, editor. *Ecology, Evolution and Coevolution*. Berlin/Heidelberg, Germany: Springer.

Soler M, 2017b. Begging behaviour, food delivery and food acquisition in nests with brood parasitic nestlings. In: Soler M, editor. *Avian Brood Parasitism Behaviour, Ecology, Evolution and Coevolution*. Cham, Switzerland: Springer. 493–515.

Soler M, FernÄndez-Morante J, Espinosa F, MartÕn-Vivaldi M, 2012. Pecking but accepting the parasitic eggs may not reflect ejection failure: the role of motivation. *Ethology* **118**:662–672.

Soler M, Martinez JG, Soler JJ, Møller AP, 1995. Preferential allocation of food by magpies *Pica pica* to great spotted cuckoo *Clamator glandarius* chicks. *Behav Ecol Sociobiol* **37**:7–13.

Soler M, Ruiz-Raya F, Roncalli G, IbÄñez-àlamo JD, 2015. Nest desertion cannot be considered an egg-rejection mechanism in a medium-sized host: an experimental study with the common blackbird *Turdus merula*. *J Avian Biol* **46**:369–377.

Spencer KA, Buchanan KL, Goldsmith AR, Catchpole CK, 2003. Song as an honest signal of developmental stress in the zebra finch *Taeniopygia guttata*. *Horm Behav* **44**:132–139.

Spottiswoode CN, Stevens M, 2010. Visual modeling shows that avian host parents use multiple visual cues in rejecting parasitic eggs. *Proc Natl Acad Sci USA* **107**:8672–8676.

Stevens M, Troscianko J, Spottiswoode CN, 2013. Repeated targeting of the same hosts by a brood parasite compromises host egg rejection. *Nat Commun* **4**:2475.

Stokke BG, Moksnes A, Røskaft E, 2005. The enigma of imperfect adaptations in hosts of avian brood parasites. *Ornithol Sci* **4**:17–29.

Thompson JN, 2005. *The Geographic Mosaic of Coevolution*. Chicago (IL): University of Chicago Press.

Thornton A, Lukas D, 2012. Individual variation in cognitive performance: developmental and evolutionary perspectives. *Philos Trans R Soc B Biol Sci* **367**:2773–2783.

Thorogood R, Davies NB, 2016. Combining personal with social information facilitates host defences and explains why cuckoos should be secretive. *Sci Rep* **6**:10–15.

Tryjanowski P, Morelli F, Osiejuk TS, Møller AP, 2018. Functional significance of cuckoo *Cuculus canorus* calls: responses of conspecifics, hosts and non-hosts. *PeerJ* **6**:e5302.

Welbergen JA, Davies NB, 2012. Direct and indirect assessment of parasitism risk by a cuckoo host. *Behav Ecol* **23**:783–789.

West-Eberhard MJ, 2003. *Developmental Plasticity and Evolution*. Oxford: Oxford University Press.

Yang C, Liang W, Møller AP, 2017. Egg color polymorphism in brood parasites and their hosts: adaptation and evolution. In: Soler M, editor. *Avian Brood Parasitism Behaviour, Ecology, Evolution and Coevolution*. Cham, Switzerland: Springer. 345–61.