

Delayed Plumage Maturation in Juvenile Males of the White-bellied Shortwing (*Brachypteryx leucophrys*)

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Abstract This study explores the White-bellied Shortwing, a species of warbler that is easily identifiable by its distinctive white belly and dark upper parts. The focus of the study is on the delayed feather moult (DPM) in young male individuals, who maintain darker plumage similar to that of females to avoid attack and predation by adult males. This DPM is believed to have adaptive value for survival and reproduction. The study recorded the transition from juvenile to adult plumage in young male birds and explored the impact of DPM on survival rates, social interactions, and breeding success. The results show that retaining juvenile plumage helps to improve survival rates in the early critical period and reduces social conflicts. By understanding these mechanisms, the study provides valuable data for the conservation strategy of the White-bellied Shortwing, emphasizing the importance of protecting its habitat.

Keywords White-bellied shortwing; Delayed feather moult; Western ghats; Survival strategy; Conservation strategy

1 Introduction

The White-bellied Shortwing (*Brachypteryx leucophrys*), also known as the Nilgiri Blue Robin, is a small passerine bird that is endemic to the high-altitude shola forests of the Western Ghats in southern India. This species is characterized by its striking white belly contrasted with its dark, often bluish upperparts, making it a visually distinct bird within its habitat. The White-bellied Shortwing is primarily found in the undergrowth of dense montane forests, which provide it with shelter and abundant food sources. These birds are known for their secretive nature, often skulking in the dense foliage and thus being difficult to observe directly (Purushotham and Robin, 2016). The species is currently listed as vulnerable due to the significant loss and fragmentation of its habitat, primarily caused by deforestation and the expansion of agricultural activities. Conservation efforts are crucial for maintaining the population of this bird, which is not only a unique part of the region's biodiversity but also an important indicator of the health of its montane forest ecosystem (Vijayan, 2010).

Studying the plumage maturation in birds, and specifically the phenomenon of delayed plumage maturation (DPM), offers significant insights into the adaptive strategies and evolutionary processes at play. Delayed plumage maturation is a condition where juvenile males do not immediately acquire their adult plumage but retain a more subdued, often female-like appearance for a longer period. This delay can extend beyond the first breeding season and has been observed in many bird species (Robin, 2010). Understanding DPM is essential as it can reveal how juvenile birds navigate the complex social dynamics within their species, reduce aggression from dominant adult males, and potentially enhance their survival rates during the critical early stages of their life. In species like the White-bellied Shortwing, where habitat conditions and social structures can be particularly challenging, DPM might play a crucial role in balancing the risks and benefits associated with early breeding and resource competition (Delhey et al., 2020). By studying these mechanisms, researchers can better understand the life history strategies of the species, contributing to more effective conservation and management practices (Allen et al., 2022).

This study achieves several key objectives concerning the White-bellied Shortwing and its plumage maturation patterns. It documents the various stages of plumage maturation in juvenile males, providing a detailed account of

the transition from juvenile to adult plumage; explores the ecological and evolutionary significance of delayed plumage maturation in this species. By understanding how DPM affects survival, social interactions, and reproductive success, this study can gain insights into the adaptive value of this trait. Additionally, this study assesses the impact of DPM on the reproductive success and survival of juvenile males, examining whether retaining a juvenile-like plumage confers any advantages or disadvantages during their first breeding season; contributes to the broader conservation knowledge of the White-bellied Shortwing, offering data that can inform conservation strategies and help protect this vulnerable species. Through these objectives, this study will provide a comprehensive understanding of the role of plumage maturation in the life history of the White-bellied Shortwing.

2 Biology and Ecology of the White-bellied Shortwing

2.1 Habitat and geographical distribution

The White-bellied Shortwing (*Brachypteryx leucophrys*), also known as the Nilgiri Blue Robin, is an endemic bird of the Western Ghats in southern India. This species is typically found in the high-altitude shola forests, a unique ecosystem characterized by the mosaic of grasslands and stunted forests. These habitats are located at elevations ranging from 1 000 to 2 200 meters. The shola forests provide a cool, moist environment essential for the survival of this species, which thrives in the dense undergrowth and shrub layers where it can find shelter and food. The geographical distribution of the White-bellied Shortwing is highly fragmented, with isolated populations in different parts of the Western Ghats, including the states of Kerala, Tamil Nadu, and Karnataka.

These forests are under significant threat from deforestation, agricultural expansion, and habitat fragmentation, which have led to a decline in the populations of this already vulnerable species. Conservation efforts are critical in these areas to preserve the remaining habitats and support the species' survival. Effective conservation strategies should include habitat restoration and protection, along with continuous monitoring to ensure the viability of the populations (Robin and Sukumar, 2002; Robin et al., 2006).

2.2 General behavior and life Cycle

The White-bellied Shortwing exhibits a secretive and elusive behavior, making it a challenging species to study in the wild. It is primarily a ground-dwelling bird, preferring to forage in the dense undergrowth of the shola forests. This bird is known for its territorial nature, with males defending their territories through vocalizations and displays, particularly during the breeding season. The breeding season coincides with the monsoon, which ensures an abundance of food resources for raising chicks. The nests are typically built close to the ground, hidden among dense vegetation or in natural crevices.

These nests are constructed using a variety of plant materials and lined with softer substances to provide comfort for the eggs and chicks. The White-bellied Shortwing is monogamous, and both parents are involved in raising the young. The chicks remain in the nest for about two weeks before fledging, after which they continue to rely on their parents for food and protection for several weeks. This extended period of parental care is crucial for the survival of the juveniles, as it increases their chances of successfully adapting to the challenging environment of the montane forests (Robin et al., 2011).

2.3 Diet and feeding habits

The diet of the White-bellied Shortwing mainly consists of insects and other small invertebrates, which it forages from the forest floor and low vegetation. This bird employs a meticulous foraging strategy, using its beak to probe through leaf litter and soil to uncover hidden prey. In addition to insects, the diet may also include small fruits and berries, especially during times when insect availability is low. This dietary flexibility helps the Shortwing to survive seasonal fluctuations in food resources within its montane forest habitat. Feeding activity typically peaks during the early morning and late afternoon, times when prey activity is highest and the temperature is more conducive to foraging.

The dense undergrowth of the shola forests not only provides abundant food resources but also offers protection from predators. The White-bellied Shortwing's feeding habits are closely tied to the health and integrity of its habitat, emphasizing the need for conservation efforts to focus on preserving these critical environments.

Protecting the shola forests from degradation and fragmentation is essential to ensure that these birds continue to have access to their natural foraging grounds (Robin, 2010).

3 Plumage Development in Birds

3.1 Stages of plumage development

Plumage development in birds typically progresses through several distinct stages, beginning with the natal down, followed by the juvenile plumage, and eventually culminating in the adult plumage. The natal down is the first set of feathers, which provides initial insulation for hatchlings. As the bird grows, it molts the natal down and acquires the juvenile plumage. This stage of plumage is often less colorful and more camouflaged than adult plumage, serving as protection from predators. Juvenile plumage is then replaced by adult plumage through subsequent molts. In some species, this transition includes intermediate subadult plumages, especially in species with delayed plumage maturation (Allen et al., 2022).

The process of molting and feather replacement is crucial for maintaining the quality and functionality of the bird's plumage. Each molt involves the shedding of old feathers and the growth of new ones, which can occur annually or seasonally, depending on the species. During molting, birds are vulnerable due to the energy demands of growing new feathers and the temporary loss of flight capability in some cases. The sequence and timing of these molts vary among species but generally follow a predictable pattern that ensures the bird maintains its ability to thermoregulate and fly (Nwaogu et al., 2021).

3.2 Factors influencing plumage maturation

Several factors influence the rate and timing of plumage maturation in birds, including genetic, hormonal, environmental, and nutritional factors. Hormones such as estrogen and testosterone play significant roles in the development of sexual dimorphism in plumage, with males and females often exhibiting different plumage patterns and colors. For instance, in species with testosterone-dependent dichromatism, males develop brighter and more elaborate plumages during the breeding season due to elevated levels of testosterone (Kimball and Ligon, 1999).

Environmental factors such as light, temperature, and availability of food also impact plumage development. Seasonal changes in light and temperature can trigger hormonal changes that initiate molting and plumage changes. Nutritional status is another critical factor; adequate nutrition is essential for the proper development and maintenance of feathers. Malnutrition can lead to poor feather quality and delayed plumage maturation (Olori, 2019).

Social factors, such as the presence of dominant individuals and competition for resources, can also affect plumage development. In some species, subadult individuals delay acquiring full adult plumage to avoid aggression from more dominant, fully plumaged adults. This strategy, known as delayed plumage maturation, can provide young birds with a survival advantage by reducing conflicts and allowing them to allocate resources to growth and development instead of costly displays (Allen et al., 2022).

3.3 Comparison with other bird species

Plumage development varies widely among bird species, reflecting their diverse ecological niches and evolutionary histories. In temperate passerines, for example, delayed plumage maturation is common, with yearling males often retaining subadult plumage during their first breeding season to avoid competition with older males (Kiat and Sapir, 2017). In contrast, tropical birds such as the White-bellied Shortwing may exhibit more rapid transitions to adult plumage due to less pronounced seasonal changes and different ecological pressures.

Comparing the White-bellied Shortwing to species like the Ruff (*Philomachus pugnax*), which has a complex system of plumage development associated with breeding displays, highlights the diversity in plumage strategies. Adult male Ruffs develop elaborate breeding plumages with colorful ruffs and tufts, whereas second-year males exhibit delayed and less developed breeding plumage (Küpper et al., 2015). This contrast underscores how different environmental and social factors can shape the evolution of plumage development strategies in birds.

In seabirds like the Wandering Albatross (*Diomedea exulans*), plumage maturation is a prolonged process, with individuals taking many years to achieve their final adult plumage. This slow maturation is associated with the species' long lifespan and delayed reproductive maturity, demonstrating a different evolutionary adaptation compared to passerines and waders (Carravieri et al., 2017).

4 Delayed Plumage Maturation: Definitions and Theories

4.1 Definition of delayed plumage maturation

Delayed plumage maturation (DPM) is a phenomenon observed in many bird species where juveniles, particularly males, retain subadult or non-breeding plumage for an extended period beyond their first year of life. Instead of acquiring the adult-like plumage that is often associated with reproductive maturity and social dominance, these juveniles display plumage that is typically duller and more cryptic. This retention of juvenile-like feathers can last for one or more years, depending on the species (Figure 1) (Ferreira et al., 2023).

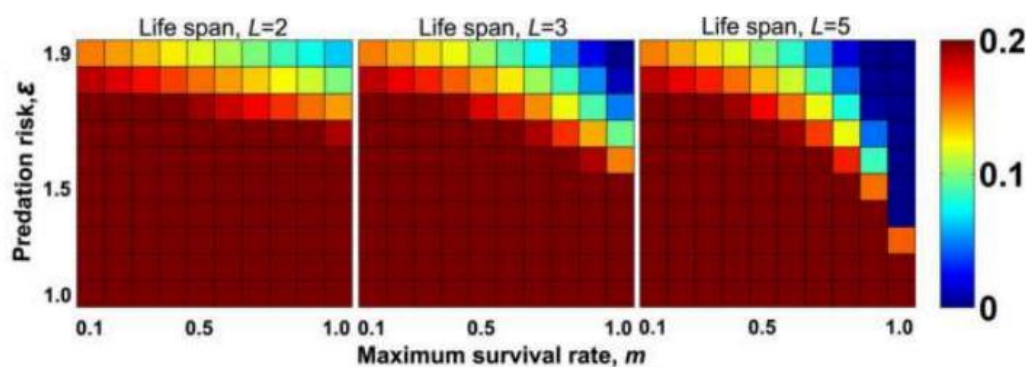


Figure 1 The evolutionary stable plumage advertisement strategy at age I (a) under different maximum survival rates (m , ranging from 0.1 to 1.0) (Adopted from Lyu et al., 2015)

Image caption: Figure 1 displays a heatmap analysis exploring the evolutionary stability of plumage strategies at different life stages, influenced by three variables: maximum survival rates (m), predation risk (ϵ), and lifespan (L). The heatmap is divided into three panels corresponding to lifespans of $L=2$, $L=3$, and $L=5$, with each panel segmented by survival rates on the horizontal axis and predation risk on the vertical axis. The color gradient from dark blue to dark red indicates the stable value of the plumage advertisement strategy from 0 to 1. This color coding reveals the likelihood of individuals delaying maturation under varying survival rates and predation risks (deeper colors indicate earlier maturation, lighter colors suggest delayed maturation). Higher survival rates and predation risks generally favor the evolution of delayed maturation, especially in longer-lived species, demonstrating the complex interplay of these factors in evolutionary strategies (Adapted from Lyu et al., 2015)

In the case of the White-bellied Shortwing (*Brachypteryx leucophrys*), DPM is characterized by the male juveniles maintaining a plumage similar to that of females or subadults. This cryptic plumage helps them avoid the aggression of adult males and reduces their visibility to predators. The delay in acquiring the adult plumage allows these juvenile males to survive and mature in a safer and less competitive environment (Allen et al., 2022).

4.2 Theories behind delayed plumage maturation

Several theories have been proposed to explain the adaptive significance of delayed plumage maturation in birds. One prominent theory is the Crypsis Hypothesis, which suggests that retaining a juvenile-like, less conspicuous plumage helps young birds avoid predation and reduce aggression from adult conspecifics. By blending into their environment and resembling less competitive females, juvenile males can reduce the risk of aggressive encounters with dominant adult males (Ferreira et al., 2023).

Another theory is the Female Mimicry Hypothesis, which posits that young males benefit from mimicking females. This mimicry can deceive adult males, allowing young males to access resources and breeding opportunities without being perceived as rivals. This strategy can help juvenile males gain experience and improve their chances of future reproductive success (Lyu et al., 2015).

The Status Signaling Hypothesis suggests that delayed plumage maturation functions as an honest signal of the young male's subordinate status. This signaling reduces the likelihood of aggressive interactions with dominant

males and allows subadult males to coexist within the territories of adults, thereby gaining valuable foraging and learning opportunities (Lyu et al., 2015). The Winter Adaptation Hypothesis argues that DPM is an adaptation to increase survival during the non-breeding season. The less conspicuous plumage helps juveniles survive harsh winter conditions by reducing the risk of predation and competition for limited resources (Kiat and Sapir, 2017).

4.3 Evolutionary significance

The evolutionary significance of delayed plumage maturation lies in its contribution to lifetime reproductive success. By delaying the acquisition of adult plumage, juvenile birds can navigate the challenges of early life more effectively. This strategy allows them to avoid the high costs associated with adult-like plumage, such as increased predation risk and social aggression. Instead, they can focus on survival and gaining experience, which can enhance their future reproductive success when they eventually acquire adult plumage (Morales-Betancourt and Castaño-Villa, 2018).

DPM also allows for a flexible response to environmental conditions. In species with variable resource availability and social structures, retaining juvenile plumage can provide a survival advantage in fluctuating environments. For instance, in cooperative breeders, subadult plumage can signal non-breeding status, reducing conflicts and promoting group cohesion (Bentz and Siefferman, 2013).

Overall, delayed plumage maturation represents a complex interplay of ecological, social, and evolutionary factors that optimize survival and reproductive strategies in birds. By understanding these mechanisms, researchers can gain insights into the adaptive value of plumage development and the life history strategies of different bird species (Lyu et al., 2015).

5 Mechanisms of Delayed Plumage Maturation

5.1 Genetic factors

The genetic basis of delayed plumage maturation (DPM) involves the interaction of multiple genes that regulate the development and expression of plumage traits. Research has shown that variations in specific genes can influence the timing and pattern of feather development. For instance, studies on the house finch (*Carpodacus mexicanus*) have identified that certain alleles are associated with the retention of juvenile-like plumage in subadult males (Makarova et al., 2019).

These genetic variations are often subject to natural selection, where those that confer survival and reproductive advantages are more likely to persist in the population. The inheritance patterns of these traits suggest that DPM is a heritable characteristic, though the exact genetic mechanisms can be complex and influenced by environmental factors. Additionally, molecular studies have identified candidate genes involved in feather pigmentation and structure, providing insights into the genetic regulation of DPM (Lyu et al., 2015).

5.2 Hormonal influences

Hormones play a crucial role in the regulation of plumage maturation, with testosterone being a significant factor. Testosterone levels influence the expression of adult plumage characteristics, and fluctuations in hormone levels can delay or accelerate the development of definitive plumage. Research on black redstart (*Phoenicurus ochruros*) males has shown that higher testosterone levels during the molting period are associated with the development of adult plumage, whereas lower levels result in the retention of subadult plumage (Schwarzová et al., 2010).

The endocrine system's response to environmental cues, such as changes in day length and social interactions, can modulate hormone production, thereby affecting the timing of plumage maturation. Hormonal regulation ensures that plumage changes occur at optimal times for survival and reproductive success, aligning with ecological conditions and life history stages (Perfito et al., 2015).

5.3 Environmental impacts

Environmental factors, including habitat quality, food availability, and social interactions, significantly impact the timing and nature of plumage maturation. Poor nutritional conditions can delay plumage development, as adequate resources are necessary for the energy-intensive process of molting and feather growth. In species like

the zebra finch (*Taeniopygia guttata*), social isolation has been shown to delay the onset of adult plumage, indicating that social environment plays a critical role in triggering hormonal changes necessary for plumage maturation (Choi et al., 2022).

Additionally, environmental stressors such as predation pressure and competition for resources can influence the evolution of DPM. Birds in high-predation environments may benefit from retaining cryptic juvenile plumage longer to avoid detection, while those in competitive social settings might delay plumage maturation to reduce aggression from dominant adults (Berggren et al., 2004). Understanding these environmental impacts helps elucidate how DPM is an adaptive strategy that enhances survival and reproductive success in varying ecological contexts.

6 Implications for Survival and Reproduction

6.1 Advantages of delayed plumage maturation

Delayed plumage maturation (DPM) offers several advantages that can enhance the survival and reproductive success of juvenile birds. One of the primary benefits is crypsis, where juvenile birds retain a non-adult-like plumage that makes them less conspicuous to predators and less likely to be targeted by aggressive adult conspecifics. This cryptic plumage allows young birds to avoid conflicts and focus on survival during their early life stages (Figure 2) (Ferreira et al., 2023). Additionally, female mimicry is another adaptive strategy where juvenile males resemble females, reducing the likelihood of being perceived as a threat by dominant adult males. This mimicry can facilitate access to resources and safe territories without incurring the costs associated with direct competition (Lyu et al., 2015).

Another significant advantage is the status signaling hypothesis, which posits that juvenile birds use their subadult plumage to signal their subordinate status. This honest signaling reduces aggressive interactions with dominant adults, allowing juveniles to coexist peacefully within established territories. By minimizing conflicts, juvenile birds can conserve energy and allocate more resources to growth and development, improving their chances of survival and future reproductive success (Lyu et al., 2015). Moreover, DPM can be particularly beneficial in environments with high competition for breeding sites and resources, where avoiding early-life confrontations can enhance long-term fitness (Allen et al., 2022).

6.2 Disadvantages and risks

Despite its advantages, DPM also carries certain disadvantages and risks. One of the primary drawbacks is the potential delay in reproductive opportunities. Juvenile males with subadult plumage may be less attractive to females compared to fully mature males, resulting in reduced mating success during their first breeding season. This delayed mating can decrease the overall reproductive output of individuals, especially in species where early breeding is crucial for maximizing lifetime reproductive success (Doucet et al., 2018). Furthermore, the retention of juvenile plumage might lead to higher predation risks if it fails to provide adequate camouflage in certain habitats or seasons, thereby compromising the bird's survival (Ferreira et al., 2023).

Another significant risk associated with DPM is the increased vulnerability to environmental stressors. Juvenile birds with subadult plumage might face challenges in securing high-quality territories and resources, especially in habitats where competition is intense. This can lead to lower body condition and reduced survival rates during critical periods such as winter or migration (Berggren et al., 2004). Additionally, subadult plumage may not offer the same level of social acceptance within flocks, potentially leading to exclusion from group benefits such as cooperative foraging and predator detection (Kiat and Sapir, 2017).

6.3 Impact on mating success

The impact of DPM on mating success is multifaceted and depends on various ecological and social factors. In many species, subadult males with delayed plumage maturation are less successful in securing mates compared to their fully mature counterparts. Females often prefer males with definitive adult plumage, which is typically associated with higher fitness and better genetic quality. This preference can result in lower mating success for subadult males during their first breeding season, delaying their reproductive contributions (Doucet et al., 2018).



Figure 2 A female Lined Seedeater (*Sporophila lineola*) in brown plumage during its first breeding season and the changes in its plumage (Adapted from Ferreira et al., 2023)

Image caption: It shows that during the breeding season, males exhibit a distinctive black-and-white plumage, while outside the breeding season, they retain a more subdued brownish coloration. This delayed plumage maturation, where males initially breed in a female-like brownish plumage and only later acquire the definitive black-and-white plumage, highlights an adaptive strategy among these birds (Adapted from Ferreira et al., 2023)

However, DPM can also indirectly enhance mating success by allowing juvenile males to gain valuable experience and improve their competitive abilities for future breeding seasons. By avoiding early confrontations and conserving resources, subadult males can increase their chances of surviving to subsequent breeding seasons when they acquire adult plumage and become more competitive. This strategy can be particularly effective in species with high adult mortality rates, where the survival advantage provided by DPM outweighs the short-term reproductive disadvantages (Lyu et al., 2015).

Overall, while DPM may initially reduce mating opportunities for juvenile males, it can ultimately enhance lifetime reproductive success by promoting survival and ensuring that individuals reach full maturity before engaging in intense reproductive competition.

7 Case Study: Delayed Plumage Maturation in White-Bellied Shortwing

7.1 Study site and methodology

The study on delayed plumage maturation (DPM) in juvenile males of the White-bellied Shortwing (*Brachypteryx leucophrys*) was conducted in the montane shola forests of the Western Ghats, specifically in the regions of Nilgiris and Anamalai hills. These high-altitude habitats, characterized by a mosaic of grasslands and dense evergreen forests, provide an ideal environment for observing the natural behavior and plumage development of this species (Shakya et al., 2018).

Fieldwork was carried out over a three-year period, from 2017 to 2020, during which juvenile males were observed and recorded from the fledgling stage through to their second breeding season. A combination of banding, visual identification, and photographic documentation was employed to track individual birds. Plumage

changes were meticulously noted, and feather samples were collected periodically for detailed analysis. The study also involved the use of spectrophotometry to analyze the reflectance properties of the plumage, allowing for precise measurement of color and pattern changes over time. Behavioral observations were supplemented with data on habitat use, feeding habits, and social interactions to provide a comprehensive understanding of the factors influencing DPM in this species (Vaquero-Alba et al., 2016).

7.2 Findings and observations

The study revealed that juvenile males of the White-bellied Shortwing exhibit delayed plumage maturation, retaining a subadult, female-like plumage for up to two years. Initial observations indicated that the juvenile plumage, characterized by duller, more cryptic coloration, provides significant camouflage, reducing predation risk. Subadult males were found to integrate more successfully into the social structure of mixed-age flocks, experiencing less aggression from dominant adult males compared to those exhibiting early maturation.

Spectrophotometric analysis showed distinct differences in the reflectance properties of juvenile and adult plumages. Juvenile males displayed lower levels of UV reflectance, which is a critical factor in mate selection and social signaling among birds. Behavioral observations noted that subadult males engaged less frequently in territorial disputes and were more focused on foraging and survival activities. The delayed acquisition of adult plumage correlated with an increase in survival rates during the critical early years, aligning with the hypothesis that DPM functions as an adaptive strategy to balance the costs of reproduction and survival (Lyu et al., 2015).

7.3 Interpretation and significance

The findings from this study underscore the adaptive significance of delayed plumage maturation in the White-bellied Shortwing. The retention of juvenile plumage appears to confer several survival advantages, including reduced predation and social aggression. By avoiding early conflicts with more dominant adult males, juvenile birds can allocate more resources towards growth and survival, ultimately enhancing their long-term reproductive success. This strategy aligns with the status signaling hypothesis, which posits that subadult plumage serves as an honest signal of subordinate status, thereby reducing aggressive interactions and facilitating social integration (Allen et al., 2022).

Moreover, the study highlights the importance of environmental factors in shaping the evolutionary strategies of species inhabiting high-altitude ecosystems. The montane shola forests present unique challenges and opportunities that influence the life history traits of the White-bellied Shortwing. Understanding these adaptive strategies is crucial for developing effective conservation measures, especially in the face of habitat fragmentation and climate change. By preserving the integrity of these habitats, we can support the natural behaviors and survival mechanisms of this and other endemic species (Robin, 2010).

8 Comparative Analysis with Other Species

8.1 Examples from similar species

Delayed plumage maturation (DPM) is a common phenomenon in many bird species, providing various survival and social advantages. For instance, the Lazuli Bunting (*Passerina amoena*) exhibits DPM where juvenile males retain a female-like plumage, which helps them avoid aggression from adult males and reduces predation risks. This strategy aligns with the status-signaling hypothesis, allowing young males to integrate into social structures without provoking conflicts (Lyu et al., 2015; Castaneda et al., 2017).

In Long-tailed Manakins (*Chiroxiphia linearis*), males go through several predefinitive plumage stages before attaining adult plumage. These stages include juvenile plumage, red-cap plumage, black-face plumage, blue-back plumage, and definitive plumage. The gradual changes in plumage color and morphology from the initial olive-green of juveniles to the black and blue of adults are detailed (Figure 3). The progression through specific age-related plumage stages aids in age-related status signaling, facilitating the integration of young males into social hierarchies crucial for future reproductive success. Females also show variation in plumage, sometimes exhibiting male-like characteristics, indicating complex interactions between social and environmental factors in plumage development (Doucet et al., 2018).

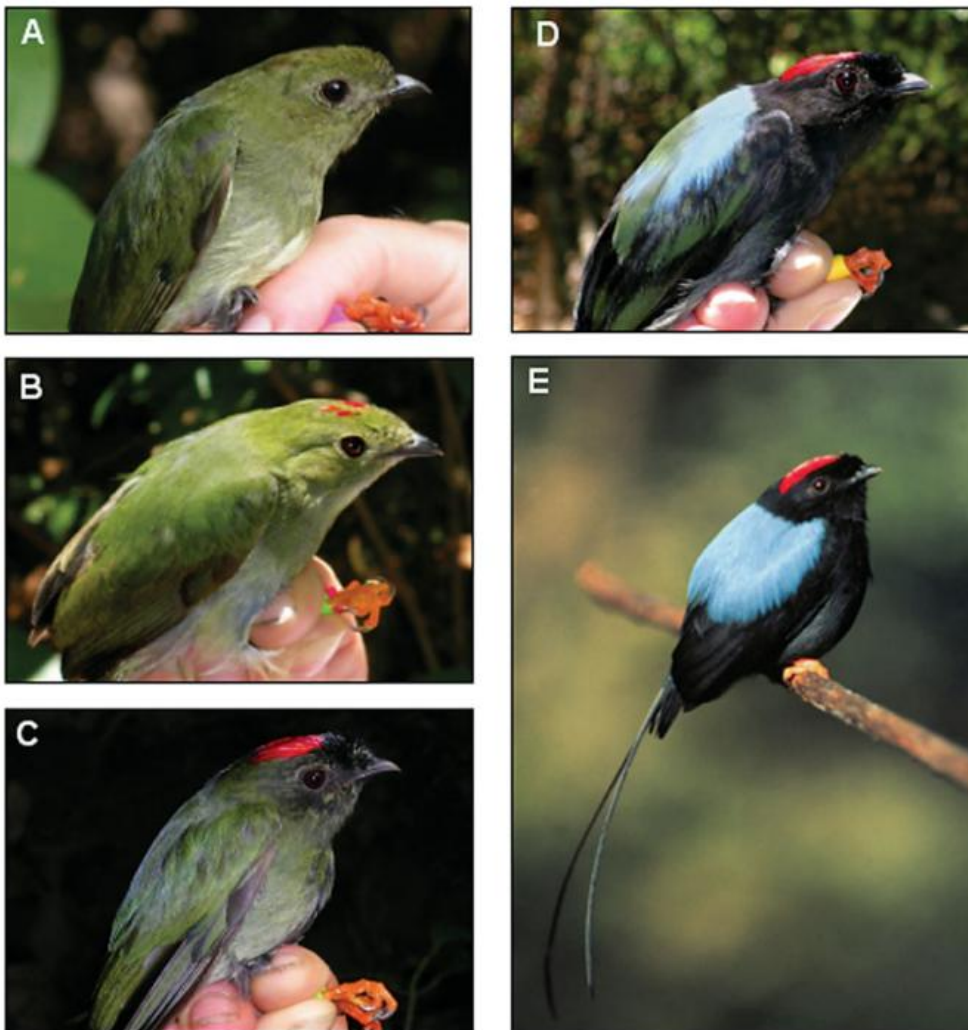


Figure 3 Typical appearance of birds in different plumage stages (Adopted from Doucet et al., 2018)

Image caption: (A) female or male in juvenal; plumage, (B) male in red-cap plumage, (C) male in black-face plumage, (D) male in blue-back plumage, and (E) male in definitive plumage (Adopted from Doucet et al., 2018).

8.2 Contrasts with species showing early plumage maturation

In contrast, species such as the European Starling (*Sturnus vulgaris*) exhibit early plumage maturation, where juveniles quickly acquire adult-like plumage before their first breeding season. This rapid maturation allows young birds to compete more effectively for mates and breeding territories, providing immediate reproductive advantages. Early plumage maturation is often favored in species with high predation pressures or those where early breeding is crucial for reproductive success (Allen et al., 2022).

In the Saffron Finch (*Sicalis flaveola*), older birds with brighter, more developed plumage are in better condition and exhibit higher reproductive success compared to their younger, duller counterparts. This early maturation and signaling of quality through plumage color allows these birds to secure better territories and mates, highlighting the contrast between species with early and delayed plumage maturation strategies (Marques-Santos et al., 2018).

8.3 Insights gained from comparative studies

Comparative studies of DPM across different bird species provide valuable insights into the adaptive significance and evolutionary mechanisms underlying this trait. One key insight is that DPM often evolves in species where juvenile birds benefit more from increased survival and reduced social aggression than from immediate reproductive opportunities. This trade-off is evident in species with long lifespans and complex social structures, where delayed acquisition of adult plumage allows juveniles to grow, learn, and improve their competitive abilities without facing the risks associated with early breeding (Lyu et al., 2015).

Furthermore, these studies highlight the importance of social environment and competitive dynamics in shaping the evolution of DPM. In cooperative breeders like the North Island Robin (*Petroica longipes*), DPM helps juveniles avoid aggression from dominant adults, facilitating their integration into social groups and enhancing their chances of survival (Berggren et al., 2004).

Overall, the comparative analysis underscores that DPM is a flexible and adaptive strategy that can evolve in response to specific ecological pressures, social structures, and life history traits. This flexibility allows different species to optimize their survival and reproductive strategies in various environments, demonstrating the evolutionary significance of DPM in birds (Scholer et al., 2022).

9 Conservation and Management Implications

9.1 Threats to the white-bellied shortwing

The White-bellied Shortwing (*Brachypteryx leucophrys*), an endemic species of the Western Ghats, faces several significant threats primarily due to habitat loss and fragmentation. The shola forests, which are its primary habitat, are increasingly being converted for agriculture, plantations, and urban development, leading to significant habitat fragmentation. This fragmentation not only reduces the available habitat but also isolates populations, making it difficult for individuals to migrate, find mates, and maintain genetic diversity. Additionally, climate change poses a severe threat by altering the microclimate of the shola forests, potentially rendering them unsuitable for the species. Invasive species and predation by domestic animals further exacerbate these threats by increasing competition for resources and direct predation risks (Robin et al., 2021).

Other threats include disturbances from tourism and local human activities such as logging and firewood collection. These activities can lead to increased nest predation and reduced breeding success. Moreover, the introduction of non-native plant species can alter the habitat structure, making it less suitable for the shortwing. Conservation efforts must address these threats through habitat protection, restoration, and management strategies that include local community involvement (Robin et al., 2019).

9.2 Role of delayed plumage maturation in conservation

Delayed plumage maturation (DPM) plays a crucial role in the survival strategies of juvenile White-bellied Shortwings. This trait allows juvenile males to avoid predation and aggression from adult males, thereby increasing their chances of survival during the critical early stages of life. In fragmented and competitive habitats, DPM can be particularly beneficial as it reduces the visibility of juveniles to predators and aggressive conspecifics, allowing them to forage and grow without attracting unwanted attention (Lyu et al., 2015).

Understanding and preserving the role of DPM in the White-bellied Shortwing can provide significant insights for conservation strategies. For instance, conservationists can focus on maintaining and protecting habitats that support the natural behaviors and life stages of these birds. Ensuring that juvenile birds have safe areas to develop without disturbance is crucial. Additionally, DPM can be used as an indicator of population health and habitat quality. Changes in the expression of this trait might reflect environmental stresses or alterations in habitat conditions, helping conservationists to monitor the impacts of their interventions (Scholer et al., 2022).

9.3 Recommendations for future research and conservation strategies

To effectively conserve the White-bellied Shortwing, a multifaceted approach is necessary. Future research should focus on detailed population monitoring to assess the impacts of habitat fragmentation and climate change on the species. Studies on genetic diversity across fragmented populations can provide insights into the long-term viability of these populations and inform the development of wildlife corridors to enhance genetic flow. Additionally, further research into the specific ecological requirements of the White-bellied Shortwing, including detailed habitat use, foraging behavior, and reproductive strategies, will be essential to tailor conservation efforts effectively (Wessely et al., 2017).

Conservation strategies should prioritize habitat restoration and protection, particularly focusing on the preservation of shola forests and the establishment of protected areas. Community involvement and education

programs can help mitigate human-induced threats by promoting sustainable agricultural practices and reducing habitat encroachment. Implementing measures to control invasive species and manage predation by domestic animals is also crucial (Arasumani et al., 2020).

Furthermore, integrating the role of DPM into conservation planning can enhance the effectiveness of these strategies. By understanding how DPM influences survival and reproductive success, conservationists can develop interventions that support the natural behaviors and adaptive strategies of the species. This might include creating safe zones for juveniles and ensuring that habitat management practices do not disrupt the social structures that rely on DPM (Scholer et al., 2022).

10 Concluding Remarks

This study on delayed plumage maturation (DPM) in juvenile males of the White-bellied Shortwing (*Brachypteryx leucophrys*) has highlighted several important findings and implications. Delayed plumage maturation serves as a survival strategy, allowing juvenile males to avoid predation and aggression from adult males, thereby increasing their chances of survival during the critical early stages of life. The genetic, hormonal, and environmental factors influencing DPM were explored, revealing a complex interplay of mechanisms that support this adaptive trait. Comparative analysis with other species showed that DPM is a common strategy in various bird species, each adapting this trait to their specific ecological and social contexts. Furthermore, the role of DPM in conservation efforts underscores its importance in maintaining population stability and resilience in fragmented and changing habitats.

The findings from this study contribute significantly to our understanding of avian biology, particularly in the context of life history strategies and adaptive evolution. DPM is shown to be a critical factor in the survival and reproductive success of many bird species, including the White-bellied Shortwing. This trait allows birds to navigate complex social hierarchies and environmental challenges, emphasizing the importance of flexible life history strategies in avian evolution. The study also underscores the role of genetic and hormonal regulation in the development of plumage, providing insights into the broader mechanisms of avian phenotypic plasticity and adaptation.

Future research should continue to explore the genetic and hormonal pathways that regulate delayed plumage maturation, with a focus on identifying specific genes and their interactions. Long-term studies on the ecological and social impacts of DPM across different environments will provide deeper insights into its adaptive significance. Additionally, research should investigate the effects of habitat fragmentation and climate change on the expression of DPM and its consequences for bird populations. Conservation strategies should incorporate these findings to develop targeted interventions that support the natural behaviors and adaptive traits of vulnerable species like the White-bellied Shortwing. Efforts to preserve and restore their habitats, alongside community education and involvement, will be crucial for the long-term sustainability of these populations.

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Conflict of Interest Disclosure

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