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SPECIAL REVIEWS IN ORNITHOLOGY

PARTIAL INCUBATION IN BIRDS: ITS OCCURRENCE, FUNCTION, AND QUANTIFICATION

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Early studies of incubation behavior acknowledged the existence of a less regular form of incubation that can occur from the beginning of egg laying to shortly after clutch completion. It has been variously termed “partial incubation” (Putnam 1949, Seel 1968, Ashkenazie and Safriel 1979), “brooding” (Barth 1955), “intermittent incubation” (Samuel 1971), “irregular incubation” (Beer 1962), or “nonrhythmic incubation” (Morton et al. 1972). This form of incubation has been described from visual observations of adults sitting on the nest less regularly, and from egg temperatures that are lower and more variable than those typically attained after clutch completion (Barth 1955, Brackbill 1958, Kendeigh 1963, Barrett 1980, Morton and Pereyra 1985). We refer to this little-understood behavior as “partial incubation” because it is characterized by a reduced amount of time during egg laying that parents sit on and warm their eggs, compared with the amount and intensity of incubation they provide later in the nesting cycle after the clutch is complete. Partial incubation is a common way for birds to initiate incubation.

The onset of incubation, the moment at which a bird begins to incubate a clutch, is a critical event in the avian nesting cycle because it has important effects on fitness, as noted more than half a century ago by David Lack (1947). Incubation onset can affect hatching success and hatching patterns (Nilsson and Svensson 1993, Wang and Beissinger 2009), nestling growth and development (Slagsvold et al. 1995, Bitton et al. 2006), fledging success (Hébert 1993, Hébert and McNeil 1999), and postfledging survival and recruitment (Cam et al. 2003). Not only can the onset of incubation affect adult reproductive rates, but it also influences and is influenced by parental body condition and survival (Hanssen et al. 2002). Yet the onset of incubation is rarely described and even less commonly quantified, and methods of determining incubation onset have not been standardized among studies or species.

In this review, we (1) clarify terminology for the onset of incubation, refine the concept of partial incubation, and summarize the prevalence of partial incubation. We then (2) examine the potential functions of partial incubation, (3) map individual-level patterns of partial incubation from previous studies onto a recently developed typology of patterns for the onset of incubation (Wang and Beissinger 2009), and examine intraspecific variability and compare interspecific data with respect to taxonomic and ecological diversity. We also (4) provide a standardized method for determining the individual onset of full incubation, using complete records of nest attendance or incubation from the start of laying to beyond clutch completion. Our goal is to show how data from disparate studies can be used to test hypotheses about the function of partial incubation. Finally, we (5) offer questions that may prove to be fertile areas of research and suggest ways to standardize future data collection and analysis to benefit common research goals.

Terminology for the Onset of Incubation

The terms “incubation” and “nest attendance” have at times been used interchangeably (Table 1). Beer (1964) defined incubation as “the process by which the heat necessary for embryonic development is transferred to an egg after it has been laid” (cited in Drent 1975). Early nest attendance that resembles incubation may not effectively warm eggs because of gradual brood-patch development (Bailey 1952, Beer 1962, Massaro et al. 2006). Beer (1962) noted that two things are being talked about and are seldom distinguished: the period during which incubation responses are shown by the parents and the period of effective incubation as indicated by the time taken for the development of an embryo. [Emphasis added]

These concepts can be operationally distinguished by techniques that observe, measure, or infer adult behavior at the nest (i.e., “nest attendance”) versus those that measure egg temperature (i.e., “effective incubation”). Not only are parental incubation behavior and embryonic development measured using different methods, but the time spent by parents in incubating behavior

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may not completely overlap with the developmental time of the embryo. This is the case for many passerines in which egg temperature stays above the developmental threshold during the female’s absences from the nest (Kendeigh 1963, Weathers and Sullivan 1989). Alternatively, time spent by parents on the nest but not in contact with the egg may not contribute to development, but may serve other purposes such as adult thermoregulation (Pendlebury and Bryant 2005) or egg cooling (Grant 1982, Walsberg and Voss-Roberts 1983).

A second conceptual duality, related to the intensity of incubation behavior, is that of “partial” versus “full.” Full incubation typically refers to the intensity of nest attendance or incubation achieved around or after clutch completion (whether measured as percentage of daily attentiveness or mean daily egg temperature). Full incubation has been variously named (Table 1) to highlight its differences from partial incubation (i.e., less regular incubation mixed with nest attendance during the laying period). The distinction between full and partial incubation is important, because the factors that affect embryo survival may differ before and after clutch completion. For example, eggs exposed to cold temperatures can survive well for several days if they were recently laid, but not if their embryos are older and well developed (Webb 1987).

A few uncommon examples deserve mention here. Full incubation can occur well before laying is complete (such as in species that hatch asynchronously), but species that hatch asynchronously may still display lower levels of incubation during the early laying period (Grenier and Beissinger 1999). Species with a clutch size of one may also display partial incubation, because a plateau in the daily proportion of time spent in incubation (Massaro et al. 2006) or in mean daily egg temperatures (Barrett 1980) may occur much later than the day of egg laying.

It may often be useful to consider partial incubation behavior separately for day and night, because diurnal and nocturnal nest attendance or incubation often differ (Wilson and Verbeek 1995, Clotfelter and Yasukawa 1999, Hepp 2004). Diurnal measurements could start and end with the active day, as determined by the behavior of the adult; they could follow a fixed period or be determined by the length of civil twilight. Nocturnal measurements would then simply be the complement of the times circumscribed by diurnal measurements. Some researchers may prefer to use a 24-h period, as would be appropriate for polar-breeding species.

### THE PREVALENCE OF PARTIAL INCUBATION

We conducted a literature search using the terms “partial incubation” and “incubation onset” in the Web of Science and in the full text of journals in the Searchable Ornithological Research Archive (SORA). The search resulted in 97 papers with information on the onset of incubation in 103 species—some of which were studied multiple times, to yield a total of 123 incubation onset samples (online Appendix; see Acknowledgments). We used information on onset as presented by the authors’ own definitions or calculations, or as judged from data shown in published tables and figures. If partial or

<table>
<thead>
<tr>
<th>Table 1. Terms used to describe partial and full incubation.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Partial</strong></td>
</tr>
<tr>
<td>Earlier incubation, partial incubation of first eggs lying in the nest</td>
</tr>
<tr>
<td>Brooding</td>
</tr>
<tr>
<td>Irregular incubation</td>
</tr>
<tr>
<td>Partial incubation</td>
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<tr>
<td>Partial incubation</td>
</tr>
<tr>
<td>Intermittent incubation</td>
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<tr>
<td>Nonrhythmic</td>
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<tr>
<td>Partial incubation</td>
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<tr>
<td>—</td>
</tr>
<tr>
<td>Incubation <em>sensu stricto</em>, any application of heat to the eggs</td>
</tr>
<tr>
<td>Laying-stage nest attendance</td>
</tr>
<tr>
<td>Any nest attendance or incubation before the onset of full incubation</td>
</tr>
</tbody>
</table>
full onset was not specified by the author(s), we used the earliest day of any nest attendance or incubation as the onset of partial incubation, and the first day that attentiveness or egg temperature reached approximately the mean level after clutch completion as the onset of full incubation. We also abstracted data on developmental mode, hatching pattern, sample size for the onset of incubation, field and statistical methods, and the egg with which collection of incubation data started (online Appendix).

Partial incubation appears to be common during the laying period. Within studies that examined the onset of full incubation in 103 species, 50 species (48.5%) exhibited partial incubation. Among those species that exhibited partial incubation, a disproportionate number ($\chi^2 = 8.35, df = 2, P = 0.015$) initiated partial incubation on the day the first egg was laid (27 species, 54.0%), compared with those that started on the day the second egg was laid (13 species, 26.0%) or later (10 species, 20.0%). Thus, partial incubation is common and often begins with the laying of the first egg.

Methods of data collection influenced whether partial incubation was detected. The percentage of samples that detected partial incubation was greater when data collection began on the day the first egg was laid compared with later in the laying sequence (27.6% vs. 16.3%, $\chi^2 = 3.6, df = 1, P = 0.057$), as well as when data collection was continuous (e.g., egg temperature recordings) rather than discontinuous (e.g., nest checks) (29.3% vs. 14.6%, $\chi^2 = 6.0, df = 1, P = 0.014$). Seventy-seven percent of samples using both criteria ($n = 20$ of 26) detected partial incubation.

The body of literature on incubation onset is not a random sample. Passerines dominated the data set (67 of 123 samples, 54%), but studies that used continuous data collection were most common of precocial species (12 of 27, 44%) (online Appendix). Tropical-zone species were underrepresented compared with temperate-zone species (11.4% vs. 56.1% of 123 samples). However, hatching patterns were generally evenly distributed among synchronous species, asynchronous species, and species that spanned both categories.

### Potential Functions of Partial Incubation

Many possible adaptive functions of partial incubation could be accomplished with or without the transfer of heat necessary for embryonic development (Table 2). Adaptive functions of partial incubation that would not require embryo development include increasing adult survival or reducing adult energy expenditure, preventing egg loss, and maintaining egg viability. Partial incubation that induces embryonic development could also accomplish any of these functions, because incubation usually requires nest attendance, although warm ambient temperatures can result in embryonic development in the absence of nest attendance.

**Functions that do not require incubation.**—Partial incubation may benefit adult survival or condition simply through nest attendance. The nest site may provide better protection from predators (Wiebe and Martin 1998) or a more favorable microclimate than other locations (Amat and Masero 2004, Pendlebury and Bryant 2005, D’Alba et al. 2009). For example, European tits roost in the nest during the laying period without raising eggs to incubation temperatures (Haftorn 1978, 1979, 1981). Partial incubation for this purpose does not require physical contact with the eggs; indeed, some species stand over the eggs in the nest cup (Brackbill 1958, Beer 1962, Haftorn 1978, Allen 1980, Haftorn and Reinertsen 1982).

Prolonged exposure of eggs to temperatures above physiological zero (24–27°C), the temperature below which no development occurs, but below the optimum for incubation (34–36°C), can cause abnormal embryonic development and hatching failure (Webb 1987, Meijerhof 1992). In these cases, incubation may be required to prevent insult to the embryos. Egg viability can also decrease during prolonged exposures to temperatures below physiological zero (Arnold 1993, Wang et al. 2011), perhaps because of changes in albumen pH and viscosity (Fasenko 2007). In this case, partial incubation could advance the embryo to an early stage of development that is more resistant to fluctuations in ambient temperature (Fasenko 2007). These functions predict that partial incubation should occur when ambient conditions could degrade egg viability during the laying period. However, much of the research on embryonic responses to variations in temperature has been performed on domesticated species, and more in situ studies of wild birds are needed.

**Functions that require incubation.**—All the above functions (adult survival, prevention of egg loss, and maintenance of egg viability) can also be fulfilled if partial incubation contributes to embryonic development. However, initiating or maintaining embryonic development is energetically costly to adults (Moreno et al. 1991, Wiebe and Martin 2000, Cresswell et al. 2004), creates
developmental asymmetries (Davies and Cooke 1983, Kennamer et al. 1990), and changes the relative amounts of time spent in the egg-laying, incubation, and nestling phases of the nesting cycle (Stoleson and Beissinger 1995). Thus, costs and benefits may be more complex to unravel when partial incubation initiates embryonic development.

For example, partial incubation in anseriforms and galliforms often initiates embryonic development but does not create hatching asynchrony. Hatch synchronization allows later-laid eggs of precocial species to hatch with the rest of the clutch when incubation starts during the laying period (e.g., Vince 1964, Davies and Cooke 1983, Persson and Andersson 1999). Partial incubation thus shortens the incubation period after clutch completion, which reduces the fasting period for females (Hanssen et al. 2002) at the expense of later-laid eggs that hatch in a smaller and less developed state (Davies and Cooke 1983, Persson and Andersson 1999). Anseriforms that continue to feed during the incubation period may still lose body mass (Tombre and Erikstad 1995), so a shorter incubation period would benefit adult body condition. Partial incubation may also maintain the viability of earlier-laid eggs by initiating embryo development, because waterfowl eggs lose viability under ambient conditions (Arnold et al. 1987, Arnold 1993).

Partial incubation that contributes to embryonic development creates hatching asynchrony while maintaining egg viability and preventing nest-site takeover in the Green-rumped Parrotlet (Forpus passerinus; Beissinger et al. 1998, Stoleson and Beissinger 1999). Thus, egg survival and viability immediately benefit from partial incubation, but the survival of early hatched chicks is favored over that of later hatched chicks. It is important to determine whether partial incubation starts embryonic development, in which case the effects of partial incubation can be more complex.

### METHODS OF MEASURING PARTIAL INCUBATION

The onset of incubation has been quantified in many ways (Table 3). Whether or not partial incubation is detected is highly dependent on the method of data collection. Inferences about the function of partial incubation are strongest when incubation can be distinguished from nest attendance by the simultaneous use of two data-collection methods that record continuously: real-egg temperature and nest attendance (e.g., Barrett 1980).

The ideal way to measure incubation is to obtain the temperature of a real egg in the nest (Caldwell and Cornwell 1975; Haftorn 1978, 1979, 1981; Burger and Williams 1979; Lill 1979; Zerba and Morton 1983; Haftorn and Reinertsen 1985; Morton and Pereyra 1985). However, real-egg temperatures alone are not ideal for measuring nest attendance. Thermal inertia of the egg can make the exact number, length, and starting or ending times of incubation bouts and recesses difficult to discern during high ambient temperatures (J. M. Wang and W. W. Weathers unpubl. data). Parental nest attendance may be more easily inferred from nest temperatures (Norton 1972, Afton 1980, Wilson and Verbeek 1995,
<table>
<thead>
<tr>
<th>Type of onset</th>
<th>Measured outcome</th>
<th>Interval</th>
<th>Method</th>
<th>Device</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial or full</td>
<td>Incubation</td>
<td>Continuous</td>
<td>Temperature</td>
<td>Real egg(^1)</td>
<td>Only way of determining embryonic development</td>
<td>Thermal gradients in egg, thermal inertia makes bout-length determination difficult</td>
</tr>
<tr>
<td></td>
<td>Nest attendance</td>
<td></td>
<td>Fake egg(^2)</td>
<td>Low cost, ease of use</td>
<td>Requires calibration with real egg temperatures to infer embryonic development</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nest(^3)</td>
<td>Low cost, ease of use</td>
<td>Require calibration with real egg temperatures to infer embryonic development</td>
<td></td>
</tr>
<tr>
<td>Visual</td>
<td>Observer(^4)</td>
<td>Detailed record of behavior</td>
<td></td>
<td></td>
<td>Effort-intensive. Nocturnal data difficult to obtain</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Video-recording(^5)</td>
<td>Detailed record of behavior</td>
<td></td>
<td></td>
<td>Nocturnal data difficult to obtain</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Time-lapse photography(^6)</td>
<td>Detailed record of behavior</td>
<td></td>
<td></td>
<td>Nocturnal data difficult to obtain</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Closed-circuit television(^7)</td>
<td>Detailed record of behavior</td>
<td></td>
<td></td>
<td>Nocturnal data difficult to obtain</td>
<td></td>
</tr>
<tr>
<td>Event-based</td>
<td>Event recorder(^8)</td>
<td>Ease of interpretation</td>
<td></td>
<td></td>
<td>No additional behavioral information</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Balance under nest(^9)</td>
<td>Ease of interpretation</td>
<td></td>
<td></td>
<td>No additional behavioral information</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Radiotransmitter receiver(^10)</td>
<td>Ease of interpretation</td>
<td></td>
<td></td>
<td>No additional behavioral information</td>
<td></td>
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<tr>
<td></td>
<td>Photo-resistor(^11)</td>
<td>Ease of interpretation</td>
<td></td>
<td></td>
<td>Custom made. No additional behavioral information</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weight-sensitive perch(^12)</td>
<td>Can distinguish male, female attendance</td>
<td></td>
<td></td>
<td>Custom made. No additional behavioral information</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Radio-isotopes(^13)</td>
<td></td>
<td></td>
<td></td>
<td>Custom made. No additional behavioral information</td>
<td></td>
</tr>
<tr>
<td>Full</td>
<td>Incubation</td>
<td>Discontinuous</td>
<td>Temperature</td>
<td>Daily nest checks(^14)</td>
<td>Ease of use</td>
<td>Assumee incubation absent before eggs warm, constant after</td>
</tr>
<tr>
<td></td>
<td>Nest attendance</td>
<td>Visual</td>
<td>Short-term observation(^15)</td>
<td>Ease of use and flexibility</td>
<td>Depending on coverage of laying period, may assume incubation is binary</td>
<td></td>
</tr>
</tbody>
</table>


\(^6\)Ashkenazie and Safril 1979, Derksen 1977.

\(^7\)Haftorn 1978, 1979.

\(^8\)Simons 1981.


\(^10\)Ringelman et al. 1982.


\(^12\)Marples and Gurr 1943, Gurr 1954.

\(^13\)Coulson and Woolf 1984.


Direct observations of parental behavior at nests can provide continuous records of nest attendance, as well as detailed behavioral information such as egg turning, males feeding incubating females, egg guarding or shading, and incubation shift changes. Continuous observer watches have been performed at single nests (Putnam 1949, Brackbill 1958, Brewer 1961, Skutch 1962, Davis et al. 1963) and simultaneously at multiple nests in an open environment (Inglis 1977, Burger et al. 1978). However, observer-performed watches generally do not provide nocturnal data. This is also true of time-lapse photography (Derkson 1977, Ashkenazie and Safriel 1979), video-recording (Hawkins 1986), and closed-circuit television (Haftorn 1978, 1979) unless the cameras are fitted with infrared lenses (e.g., Haftorn and Reinertsen 1982, Wang and Weathers 2009). Recent research indicates that nocturnal nest attendance can be far less regular than is often assumed (Wang and Beissinger 2009).

Event-based data collection records the time that adults enter or exit from the nest, reducing continuous monitoring to binary records of nest attendance. Investigators have used event recorders (Simons 1981), balances under the nest (Kennamer et al. 1990, Bortolotti and Wiebe 1993, Mallory and Weatherhead 1993), radiotransmitter receivers (Ringelman et al. 1982), photo-resistors (Stenger Weeden 1966), weight-sensitive perches (Marples and Gurr 1943, Gurr 1954), and radio-isotope traces (Coulson and Wooler 1984) to record nest attendance for multiple days. These data are potentially the easiest to interpret, but they typically sample nest attendance rather than incubation, which requires that a bird in the nest to be in contact with the eggs.

Sporadic data collection is less ideal for studying early incubation but is nonetheless frequently employed. The most basic method for determining the onset of incubation is by noting whether eggs are warm or cold to the touch during a routine nest check (Hann 1937, Faustin 1941, Mickey 1943, Gibb 1950, Lack and Lack 1951, Evenden 1957, Seel 1968, Howell 1979, Murray et al. 1983, Magrath 1992, Nilsson 1993, Vinuela 1997, Potti 1998, Clotfelter and Yasukawa 1999, Rowe and Weatherhead 2009, Arnold 2011). Most studies using this “once daily” method are concerned with the onset of full incubation. This method assumes that eggs are always unattended before the start of incubation, and that once incubation begins the eggs are maintained at a temperature that is warm to the touch. However, both assumptions have been falsified in studies that monitor the nest continuously from the start of egg laying. Short-term opportunistic or systematic visual observations are another method of sporadic data collection (Beer 1962, Maxson and Oring 1980, Lessells and Avery 1989, Hébert and Sealy 1992, Banbura and Zielinski 1995). Depending on their coverage of the laying period, they can pose the same problems as the “once daily” method for inferring the onset of incubation. Short-term observations are more suited to testing hypotheses applicable to full incubation (Conway and Martin 2000), rather than the development of incubation behavior over multiple days.

Multiple studies on the same species illustrate how the type of data collection influences when partial incubation is detected. An early study of the Great Tit (Parus major) reported partial incubation starting with the ninth egg (mean clutch size = 10.94, n = 112) using daily nest checks (Gibb 1950), whereas later studies using nest-cup temperatures found incubation starting from the third (Haftorn 1981) to the sixth egg (Haftorn and Reinertsen 1982). In the Mountain White-crowned Sparrow (Zonotrichia leucophrys oriantha), partial incubation started with the first egg in a study that combined daily nest checks with extensive visual observation (Morton et al. 1972), as well as when egg temperatures were recorded continuously (Zerba and Morton 1983). Thus, discontinuous data collection may agree with continuous methods if the observation window is sufficiently large.

**Survey of Patterns of Diurnal Partial Incubation**

We recently reported a wide diversity in developmental trajectories of nest attendance prior to full incubation in five passerines (Wang and Beissinger 2009), with high variation in individual trajectories within a species as well as significant variation in the relative frequencies of trajectory types among species. These individual trajectories were classified into “incubation onset patterns” using a general typology based on qualitative criteria that describe patterns of partial incubation that can be applied to all species (Fig. 1). For instance, an individual bird that started incubating with low constancy (percentage of the day incubated) and slowly increased in constancy with each succeeding day was classified as having a “slow-rise” pattern, whereas a bird that initiated incubation at low constancy and achieved the constancy of full incubation within a few days was classified as having a “rapid-rise” pattern. In both of these patterns, incubation constancy rises monotonically (Fig. 1). We termed the incubation onset patterns that rise non-monotonically “irregular,” “pulsed,” and “step” (Wang and Beissinger 2009). Additional patterns that did not have an overall rise in constancy were termed “W-shape” and “U-shape” (Fig. 1). These 11 patterns were placed into four groups based on the similarity of their incubation trajectories: rising, irregular rising, not rising, and flat (Fig. 1).

We used this typology to manually assign diurnal, full-incubation-onset patterns from published works on individuals from 7 species (n = 59 nests) in addition to the 5 species (n = 73 nests) used to derive the typology (Wang and Beissinger 2009) (Table 4). We tested whether patterns of individual onset varied by mode of development, hatching pattern, and taxonomic order. The predictions are straightforward for species in which nest attendance during the laying period is effective incubation. We predicted that precocial species with hatch synchronization (e.g., many anseriforms and galliforms; Vince 1964, Davies and Cooke 1983) would have substantial partial incubation and a slow-rise pattern. On the other hand, precocial species without hatch synchronization would be expected to have rapid-rise incubation patterns that start with the last egg of a clutch, to ensure that all eggs receive the same effective incubation. In keeping with our
FIG. 1. General patterns for characterizing the onset of full incubation according to whether or not incubation rises monotonically, whether the rise occurs continuously, and the speed and duration of rises. For all patterns, the x-axis is days or nights prior to the completion of laying or on the second consecutive day or night after full incubation (whichever came later), and the y-axis is the proportion of the day or night incubated. The patterns were categorized into four groups based on similarity: rising (flat-rise, rapid-rise, slow-rise), irregular rising (step, pulsed, irregular), not rising (W-shape, U-shape, flat-fall, falling), and flat (flat). The data examined for each nest started with the last day or night having ≤1 h of incubation (all flat sections shown are nonzero proportions). The irregular and pulsed patterns could have one or more decreases in incubation. Modified from Wang and Beissinger (2009).
TABLE 4. Intraspecific variation in full diurnal incubation-onset patterns. Numbers and percentages of individuals in each study are presented. Sample size (n) is given for each species for which data were available (total n = 132). The outcome measured by each study is shown as either nest attendance (n.a.) or incubation (inc.).

| Species                        | Measured                | Outcome              | Mode of development | Order         | Pattern       | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
|--------------------------------|-------------------------|----------------------|---------------------|---------------|---------------|------|------|------|------|------|------|------|------|------|------|------|
|                               |                         |                      |                     |               | Rising        |      |      |      |      |      |      |      |      |      |      |      |      |
| Altricial                     |                         |                      |                     |               | Flat-rise     | 12   | 2    | 3    | 6    | 2    | 1    | 1    | 5    | 2    | 12   |
|                               |                         |                      |                     |               | Rapid-rise    | 6    | 2    | 6    | 5    | 2    | 1    | 1    | 5    | 2    | 12   |
|                               |                         |                      |                     |               | Slow-rise     | 3    | 1    | 5    | 2    | 1    | 1    | 1    | 5    | 2    | 12   |
|                               |                         |                      |                     |               | Step          | 1    | 1    | 2    | 1    | 1    | 1    | 1    | 5    | 2    | 12   |
|                               |                         |                      |                     |               | Pulsed        | 1    | 1    | 2    | 1    | 1    | 1    | 1    | 5    | 2    | 12   |
|                               |                         |                      |                     |               | Irregular     | 1    | 1    | 2    | 1    | 1    | 1    | 1    | 5    | 2    | 12   |
|                               |                         |                      |                     |               | U-shaped      | 1    | 1    | 2    | 1    | 1    | 1    | 1    | 5    | 2    | 12   |
|                               |                         |                      |                     |               | W-shaped      | 1    | 1    | 2    | 1    | 1    | 1    | 1    | 5    | 2    | 12   |
|                               |                         |                      |                     |               | In rising     | 1    | 1    | 2    | 1    | 1    | 1    | 1    | 5    | 2    | 12   |
|                               |                         |                      |                     |               | Not rising    |     |     |     |     |     |     |     |     |     |     |      |

To summarize, in species in which nest attendance during the laying stage results in effective incubation, patterns of the onset of incubation reflect hatching patterns and the degree of hatching asynchrony. But these relationships break down when nest attendance in the laying stage does not correlate with effective incubation. If individual variation is as great as these data indicate, individual, environmental, and taxonomic factors may all influence developmental trajectories of incubation at different temporal scales.

**Suggestions for Reporting Incubation Data**

Standardized criteria for determining the onset of full incubation would facilitate interspecific comparisons of incubation from studies using disparate methods of quantifying incubation.
We recommend using a 90% lower confidence interval of daily or nightly attentiveness, calculated starting with the day or night after clutch completion, as a threshold for the onset of full incubation (Wang and Beissinger 2009). If egg temperatures are available, then the lower 90% confidence interval of the mean daily (or nightly) egg temperature after clutch completion could be used. This criterion is estimated in relation to the incubation behavior (or egg temperature) at each nest after the laying period, and quantifies what many studies have done implicitly by plotting daily attentiveness or mean egg temperatures through the laying and incubation periods. With the variety of continuous-data-recording technologies available today, there are few limitations on obtaining daily attentiveness during and well past the laying period.

As far as labeling when the onset of incubation occurs, researchers have used either the first egg as the reference (first, second, third, etc.) or the last egg as the reference (ultimate, penultimate, prepenultimate, etc.). The choice often depends on the species’ hatching pattern, because asynchronous species commonly begin full incubation closer to the first half of the laying period and synchronous species start full incubation in the second half of the laying period. The onset of partial incubation is often reported using the first egg as the reference, because onset is more likely to occur early in the laying period. Unfortunately, eggs that have the same label with reference to the last egg can have different numbers of eggs preceding them, depending on the clutch size. We propose a labeling protocol that incorporates both types of names (Table 5). The protocol can easily be applied to clutches of 1 to 7 or more and applies unambiguous labels to both ends of the clutch. We hope that this modified protocol will allow for easier cross-study comparisons in the future.

The causes of variation in incubation onset patterns largely remain to be determined (Wang and Beissinger 2009). These include forces that act within individuals or nests on a small temporal scale (daily changes in environmental conditions or energetic constraints on adults), among individuals or nests (age, body condition, experience), and through larger-scale environmental variation (yearly or seasonal change). Mixed models can incorporate autocorrelation in repeated observations within individuals as well as correlations across individuals that are explained by variables such as age (Diggle et al. 2002). For linear trajectories, differences in slope and elevation can be attributed to fixed effects, such as year and age, or random effects based on individual variables such as condition (Littell et al. 2006). Variables that change value daily, such as ambient temperature, humidity, and precipitation, can be incorporated as time-varying covariates. These approaches allow multiple temporal scales to be investigated simultaneously (e.g., daily, seasonal, or yearly) with “permanent” environmental effects over an individual’s lifetime.

**Fertile Areas for Future Research**

The extent and causes of partial incubation are poorly understood. Although partial incubation is more common than previously recognized, there is no consensus on what it is or what it does. Investigating proximate influences on partial incubation also addresses questions about patterns of full incubation onset. Genetic, physiological, and environmental factors will provide the underpinnings of variation in incubation onset, and may also illuminate constraints on the evolution of incubation strategies. Individual-level behavioral data related to variation in the onset of incubation could address a host of questions at both the intraspecific and interspecific levels. Does intraspecific variation in the onset of incubation correlate with the size of a species’ geographic range or with temporal variability in weather during the breeding season? Does partial incubation vary substantially within all species, or are some taxa less flexible in this trait? Additionally, does partial incubation vary with the proportion of nests lost to predators or starvation, between cavity- and open-cup-nesting species, or between species with single-sex versus biparental incubation?

At the proximate level, partial incubation can be viewed as the behavioral outcome of physiological changes during the laying period (Mead and Morton 1985, Sockman et al. 2006). A gradual increase in prolactin often accompanies a gradual increase in incubation behavior; individual trajectories of incubation constancy during egg laying should then mirror those of prolactin levels (Sockman et al. 2000). This view predicts that incubation constancy should covary with prolactin levels, which in turn may be related to individual factors, such as body condition, age, and

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**Table 5. Proposed labeling protocol for the onset of incubation.** For species with laying intervals of 1 day, labels would indicate onset for the day on which the egg is laid. For species with laying intervals greater than 1 day, labels would indicate the number of eggs in the nest at onset. For clutches of more than 7 eggs, the label “middle” would be repeated as needed for eggs laid in intermediate positions. Despite an attempt to assign fixed labels to every egg position for all clutch sizes, some ambiguity remains: labels in parentheses within a row indicate equivalent terms that may be chosen depending on the other clutch sizes in a particular study. For instance, if all clutches greater than 1 egg began full incubation with the last egg laid, the sole 1-egg clutch may be said to have an onset of incubation with the last egg laid instead of the first egg laid, for ease of comparison.

<table>
<thead>
<tr>
<th>Clutch size</th>
<th>Egg label</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (First)</td>
<td>— — — (Last)</td>
</tr>
<tr>
<td>2 First</td>
<td>— — — Last</td>
</tr>
<tr>
<td>3 First (Second)</td>
<td>— — — (Penultimate) Last</td>
</tr>
<tr>
<td>4 First Second</td>
<td>— — Penultimate Last</td>
</tr>
<tr>
<td>5 First Second (Third)</td>
<td>— (Prepenultimate) Penultimate Last</td>
</tr>
<tr>
<td>6 First Second Third</td>
<td>Prepenultimate Penultimate Last</td>
</tr>
<tr>
<td>≥7 First Second Third</td>
<td>Middle Prepenultimate Penultimate Last</td>
</tr>
</tbody>
</table>
prior breeding experience. Whether rapid behavioral changes in nest attendance or incubation are accompanied by physiological shifts in hormone levels has not been thoroughly studied (Jónsson et al. 2006). In species in which both sexes incubate, plasma prolactin levels remain high during extended absences from the nest (Vleck et al. 2000), which suggests interspecific variability in the relationship between prolactin and parental behavior. Species with biparental incubation may have onset patterns that are less tightly coupled to hormone levels.

Short-term behavioral lability in the development of incubation offers a window into the tradeoffs among adult survival, maintenance, and reproduction. Not only do daily behavioral changes reflect shifts in the balance of energy or time allotted to maintenance or reproduction, but these shifts directly affect offspring survival and quality (Wang and Beissinger 2001). As such, patterns in the onset of incubation interact with other labile reproductive traits, such as clutch size and lay date, to integrate past and current environmental conditions into a combined reproductive effort.

Solving the methodological issues for studying the onset of incubation may ultimately provide a window into the evolution of hatching patterns. Depending on the environmental conditions, either nest attendance or true incubation may be necessary to preserve egg viability. Discovering the types and patterns of early incubation may help explain latitudinal gradients in hatching asynchrony (Clark and Wilson 1981), hatchability (Koenig 1982), and clutch size (Cooper et al. 2006, Jetz et al. 2008).

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Literature Cited


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