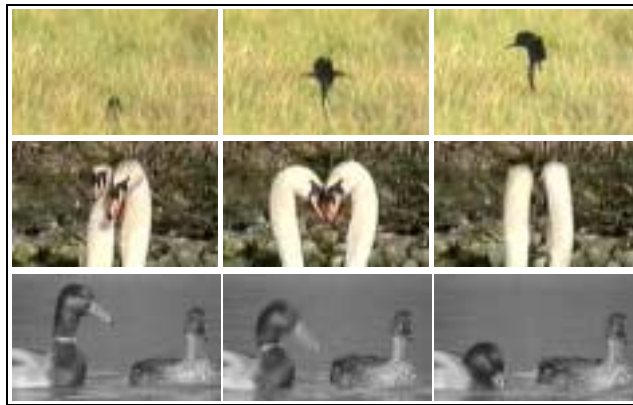# Relating Categories of Intentional Animal Motions

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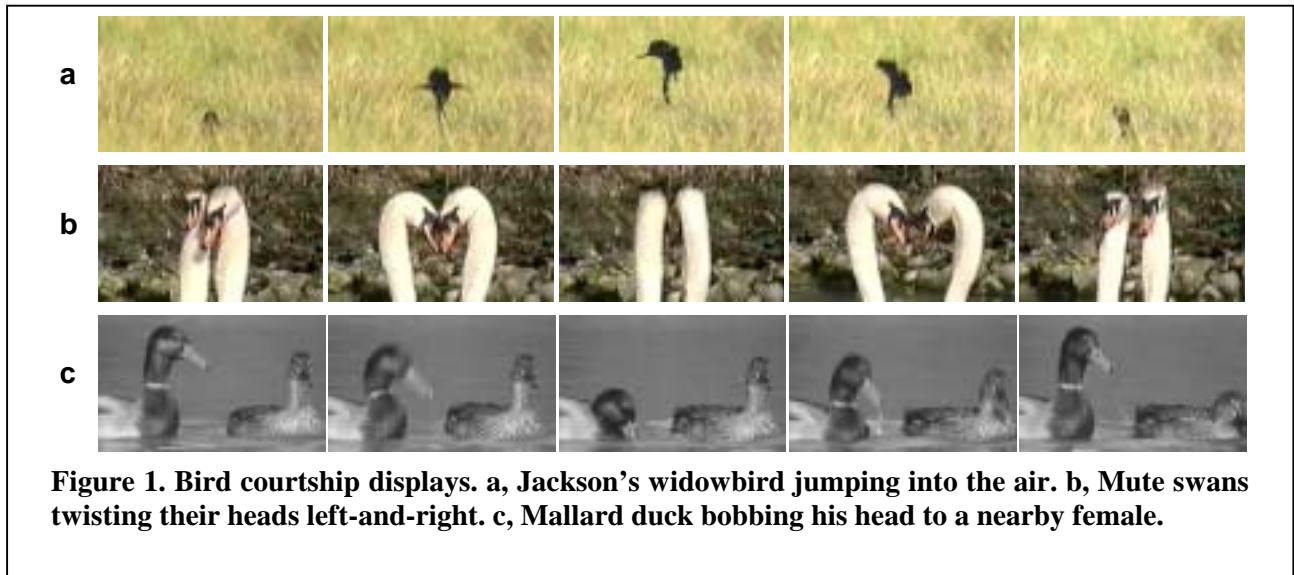
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Relating Categories of Intentional Animal Motions

The intentional movements of birds and other animals can be characterized using a very simple categorical model of motion

James W. Davis and Whitman A. Richards

Many behaviors throughout the animal kingdom consist of performing and recognizing specialized patterns of motion. From an ethological standpoint, movement is often used to recognize conspecifics, identify prey, deceive predators, and communicate. Birds seem especially well endowed with communicative display movements that are visually rich and diverse (examples are shown in Fig. 1). A common and predictable feature of such intentional display movements is rhythmic (oscillatory) repetition. For example, Mallard ducks (*Anas platyphynchos*) bob their head *up-and-down* to a female, Ruby-throated hummingbirds (*Archilochus colubris*) swing in a pendular *U-shaped path*, and Peregrine falcons (*Falco peregrinus) loop* through the air. Outside the avian domain, we also see similar repetitive movements used for communication. For instance, spiders wave their palps *up-and-down* as a form of

Figure 1. Bird courtship displays. a, Jackson's widowbird jumping into the air. b, Mute swans twisting their heads left-and-right. c, Mallard duck bobbing his head to a nearby female.

courtship, Honey bees dance in a *circle* or *figure-8* to signal the presence and location of a food source to the hive, Sceloporus lizards identify one another from *push-ups*, and chimpanzees sway from *side-to-side* as a threat (or for courtship). It is interesting that certain types of oscillatory motion patterns appear across such a variety of species.

In Table 1, we list a set of oscillatory motion patterns which appear widely throughout the animal kingdom and that in particular are used by birds as a form of display behavior. These motions are frequently reported for birds in common field guides (e.g. (Stokes 1979)). Birds that perform these motions are additionally listed in the table. Communicative displays are particularly interesting because they have intentional goals associated with them and their consistency with respect to form, speed, and rhythm makes them favorable for characterization (Morris 1957).

Table 1. Example oscillatory avian displays*

Motion	Birds
Up-and-down	Bluejay, Pileated woodpecker, Dark-eyed Junco.
Side-to-side	Snowy owl, Northern fulmar, Red-eyed vireo.
Circle	Gray phalarope, Sparrowhawk, Woodlark.
Spiral	Mourning dove, American woodcock, Isabelline wheatear.
Loop	Booted eagle, Mockingbird, Redpoll.
Undulate	Northern goshawk, Yellow-bellied sapsucker, Desert lark.
Figure-8	Piping plover, Peregrine falcon, Black-eared wheatear.
U-shuttle	Ruby-throated hummingbird, Hobby, Northern harrier.

* Three example bird species are given for each motion, though the motion may be performed by a wide variety of species.

With the commonality among species and the oscillatory similarity of the motions, it is natural to inquire how these patterns might be related. We begin by presenting a simple sinusoidal model that permits a straightforward categorization of the motions. We then show that there is an underlying ordering of these

motions based on choices of model parameters. The resulting organization is used to partition the motions into sub-categories that highlight the prominent forms of motion specialization. We also show that while particular species prefer certain patterns, the simpler movements have a wider usage *among* species.

A Simple Generative Model

The movements in Table 1 are all simple, symmetrically repetitive motions, and can be modeled as sinusoids:

$$
\begin{aligned}
x(t) &= A_x \sin(2\pi f_x t + \phi_x) &+& B_x t \\
y(t) &= A_y \sin(2\pi f_y t + \phi_y) &+& B_y t \\
z(t) &= A_z \sin(2\pi f_z t + \phi_z) &+& B_z t \qquad (1)
\end{aligned}
$$

where (x,y,z) is the 3-D Cartesian location of some point feature over time (perhaps the body in motion or a color patch on a moving body part), A is the amplitude of the wave, f is the frequency, ϕ is the phase shift, and B is the translation. The above description simply dictates the shape or path of the motion over time (i.e. the motion pattern), without specifying any time-varying dynamics. Obviously more complex dynamical models could be used, as to characterize handwriting (Hollerbach 1981), but they too must obey the underlying oscillatory nature as given by the sinusoidal model (see (Richards 1988) for additional examples of related models). Table 2 shows the parameter settings for this model needed to characterize this set of oscillatory motions (idealized in their purest, planar form).

Looking closely at the parameters in Table 2, we find very specific and limited values. For these motions, the only 2-D frequency ratios are { :1, :2} and the only relative phases (locking $\phi_x=0$ for reference) are $\{0, \pm\pi/2, \pi\}$. In particular, the phase difference relation for circular motions (circle, spiral, loop) must obey $\phi_x - \phi_y = \pm\pi/2$, for figure-8 the relation must be $2\phi_{slow} - \phi_{fast} = \{0,\pi\}$, and for U-shuttle the constraint is $2\phi_{slow} - \phi_{fast} = \pi/2$. For looping, its translation B_x is constrained by the product of its corresponding

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amplitude and frequency ($2\pi f\alpha_x$), otherwise swinging occurs. Although many other distinctive values could exist for the sinusoid parameters (e.g. $\frac{\pi}{3}$, $4f$, etc.), they are not seen in these oscillatory motions. Such special values for this model suggest that generative or structural regularities (Richards and Bobick 1988) underlie this class of movement.

In addition to the structural parameter relations described above for the qualitative pattern, there exist parameter values designed for specific stylistic variation in their performance. In the motions, stylistic information can be encoded into the amplitude and/or frequency parameters resulting in selective and immediate recognition (e.g. as used for species identity). For example, the U-shuttle movements for the Black-chinned hummingbird (*Archilochus alexandri*), Broad-tailed hummingbird (*Selasphorus platycerus*), and Calliope hummingbird (*Stellula calliope*) are performed each with differing heights ranging from about 4.5-7.5, 6-12, to 18-27.5 meters, respectively (Stokes and Stokes 1989). These motion patterns are qualitatively similar (i.e. pendular swinging), but differ in the amplitude of the height (i.e.

Table 2. Oscillatory Motions and Model Parameters											
Motion	Amplitude			Frequency			Phase			Translation		
	A_x	A_y	A_z	f_x	f_y	f_z	ϕ_x	ϕ_y	ϕ_z	B_x	B_y	B_z
Up-and-down	0	α_y	0	−	f	−	−	0	−	0	0	0
Side-to-side	α_x	0	0	f	−	−	0	−	−	0	0	0
Circle	α_x	0	α_z	f	−	f	0	−	$\pm\pi/2$	0	0	0
Spiral	α_x	0	α_z	f	−	f	0	−	$\pm\pi/2$	0	(0…]	0
Loop	α_x	α_y	0	f	f	−	0	$\pm\pi/2$	−	[0–$2\pi f\alpha_x$)	0	0
Undulate	0	α_y	0	−	f	−	−	0	−	(0…]	0	0
Figure-8	α_x	α_y	0	$f/2$	f	−	0	$0,\pi$	−	0	0	0
U-shuttle	α_x	α_y	0	$f/2$	f	−	0	$-\pi/2$	−	0	0	0

Model parameters are shown for the oscillations generated by sinusoidal functions ($X(t)=A\sin(2\pi ft+\phi)+Bt$). Values α and f correspond to variable amplitude and frequency values, respectively. Slots with − are non-applicable parameters due to corresponding zero amplitudes.

from shallow to steep). Given that these species reside in the same West Coast territory, this difference may act as an isolation mechanism (Tinbergen 1951) during interactions. We can therefore describe such
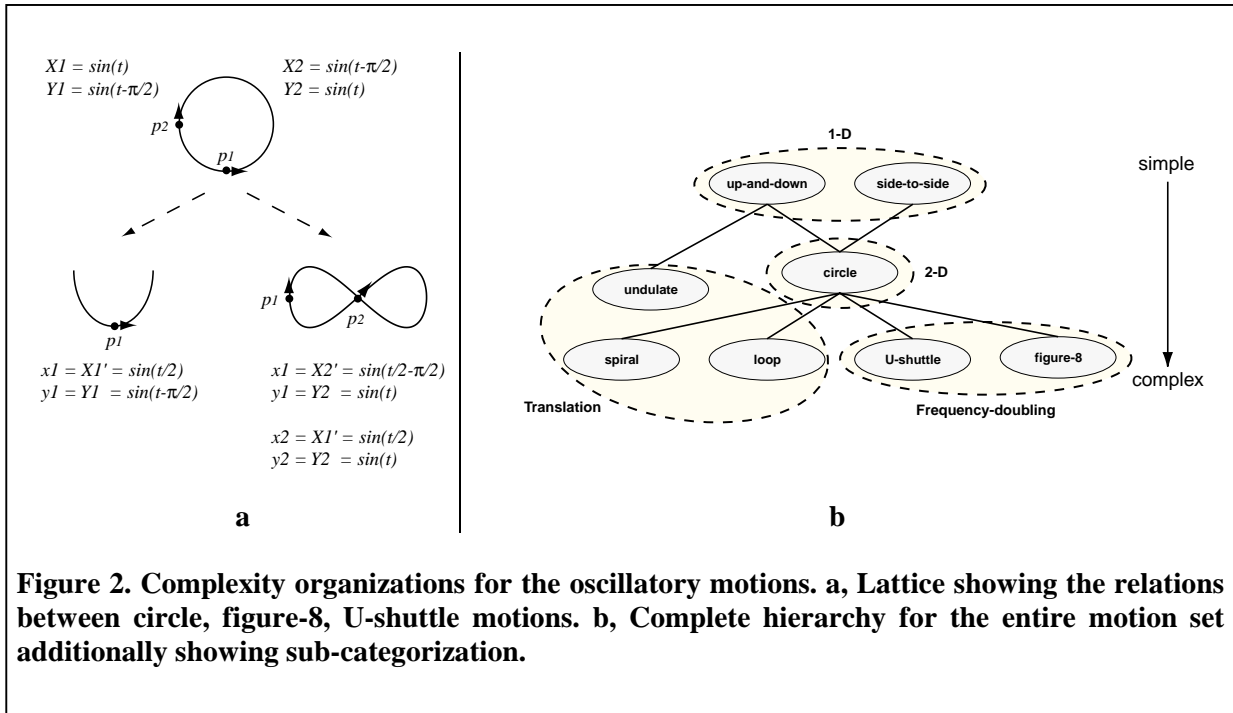
an oscillatory motion in terms of its constrained *form* (e.g. the U-shuttle) and a selective *style* (e.g. the height amplitude).

Simple vs. Complex Motions

Given the generative representation (sinusoidal model) and the structural constraints for the oscillatory patterns, we can now further organize the motions by the amount of increasing specialization in the model parameters. In terms of motion complexity, we focus on the structuring of the generative parameters rather than the performance medium (e.g. in the air, on the ground, the performing limb).

Here we make explicit the relationship between the types of structure (and motions) within the category by noticing that some motions are combinations of more primitive movements or have additional parameter components/constraints. At the top of the ordering are states of least constrained (or least structured) motion. At each level below, a dimension of specialization is incrementally imposed on the simpler patterns. The leaf nodes in the hierarchy thus show those motions most completely specified with regularities (most structured).

The least constrained movements in our set according to the model are clearly the one-dimensional up-and-down and side-to-side movements. Then adding a translation to up-and-down generates the more specialized undulation motion (up-and-down + translation). Also more specialized is 2-D circular motion, generated by combining the top-level up-and-down and side-to-side motions with a phase difference constraint of $\phi_x - \phi_y = \pm\frac{\pi}{2}$. The two possible signs of the phase difference correspond to clockwise and counter-clockwise directions. We know that both directions are possible (as exemplified by the male bridled tern that circles the female, periodically reversing direction) and that two sinusoidal generators with a single phase value ($-\frac{\pi}{2}$) flipping between the x and y functions can be utilized (see Fig. 2.a). We can recombine the individual x and y circle functions with a frequency-doubling constraint (doubling the

Figure 2. Complexity organizations for the oscillatory motions. a, Lattice showing the relations between circle, figure-8, U-shuttle motions. b, Complete hierarchy for the entire motion set additionally showing sub-categorization.

frequency in one of the two dimensions, $\frac{1}{2}f_x = f_y$) to generate both figure-8 and U-shuttle (see Fig. 2.a). This parsimonious ordering for circle, figure-8, and U-shuttle also appears in the communicative dance signals of honey bees, where species movements may transform from a simple bi-directional circle dance into either a figure-8 (by Carniolan bees) or U-shuttle (by *Apis mellifera mellifera* or *A. m. ligustica*) before converting into the classic waggle dance (von Frisch 1967). Also derived from the circle motion is spiraling and looping, which is produced by adding a translation (2-D circle + translation). Fig. 2.b shows the resulting hierarchical ordering of the entire class of motions.

With this ordering, we can derive sub-categories reflecting the prominent specializations in the motions. Noticing a common translation component, we can group together undulate, spiral, and loop into a *translation* sub-category. With a 2-D frequency ratio of 1:2, U-shuttle and figure-8 can be grouped into a *frequency-doubling* sub-category. Then circle motion represents the earliest introduction of a *2-D motion* sub-category. And lastly, the up-and-down and side-to-side movements correspond to a simple *1-D motion* sub-category. Thus, the hierarchical structure orders the individual motions and the sub-categories
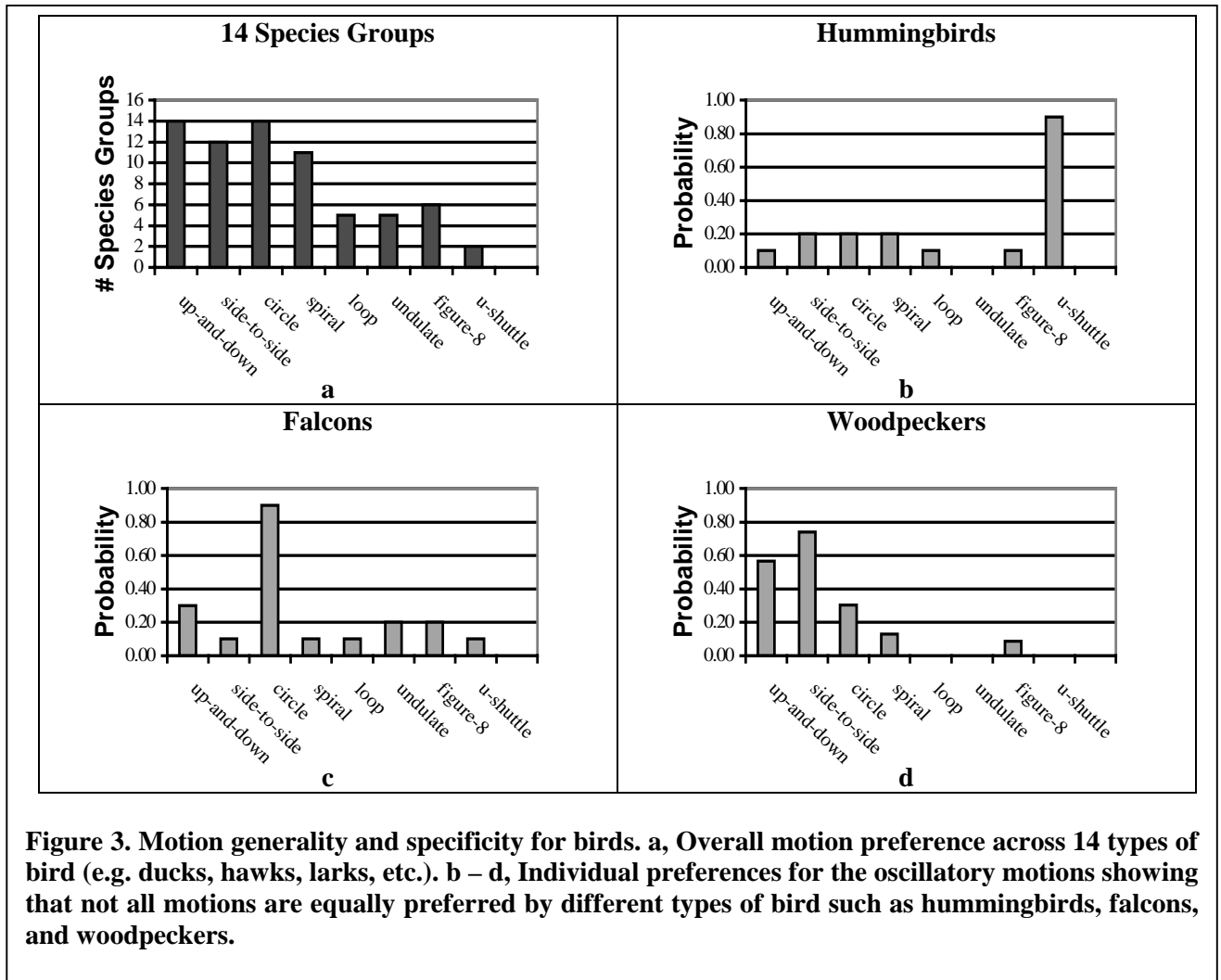
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from simple to complex in relation to their structural specializations (see Fig. 2.b). For example, up-and-down (1-D) is simpler than circle motion (2-D), which in turn is simpler than U-shuttle (2-D with frequency-doubling).

Species Generality and Specificity

When we examine the distribution of the oscillatory display motions across 14 types of birds (ducks, falcons, gulls, hawks, herons, hummingbirds, kingfishers, larks, owls, pigeons, plovers, terns, wheatears, and woodpeckers) as described in a dozen field guides, we see a biased trend favoring the *simplest* movements in the hierarchical ordering (see Fig. 3.a). Although most bird species can perform many of the movements to some degree, the relative frequency of these motions differs considerably *across* species. For example, up-and-down, side-to-side, and circle motions are quite ubiquitous across species, and not surprisingly, the more complex motions such as figure-8, U-shuttle, and loop are more infrequent. To test for a precise correlation between the ubiquity across bird species and the hierarchical organization (under the assertion that "simple movements should be more universal than complex movements") would require a thorough examination of all bird species and a comprehensive cataloguing of their behaviors – a daunting task. Our sampling of bird species, though, indicates that there indeed is a general trend: simpler oscillatory movements (1-D, 2-D) are more widespread across species than are the more complex patterns (2-D + translation, 2-D with frequency-doubling).

When we examine these motions for various individual bird species, we see that different types of birds have a tendency to prefer certain characteristic motions. This is shown in more detail in the graphs of Fig. 3.b-d, where the peaks correspond to most common oscillatory movements performed by hummingbirds, falcons, and woodpeckers. Here we see that most hummingbirds perform the *U-shuttle*, while falcons tend to fly in *circular* formations and woodpeckers particularly move *up-and-down* and *side-to-side*. The data was compiled by examining the oscillatory displays of several species for the three bird types (10 hummingbirds, 23 woodpeckers, and 10 falcons) as listed in the field guides. For each type

of bird, the species count of each motion was normalized by the number of species examined to give an

estimated probability that the motion will be exhibited by that type of bird.

Figure 3. Motion generality and specificity for birds. a, Overall motion preference across 14 types of bird (e.g. ducks, hawks, larks, etc.). b – d, Individual preferences for the oscillatory motions showing that not all motions are equally preferred by different types of bird such as hummingbirds, falcons, and woodpeckers.

Significance of Categorical Motions

As birds do not equally prefer the motions for their displays, the ubiquity of certain patterns across

species shows evidence for our notions of simplicity. These motion patterns appearing across species

reflect regularities in nature and provide useful indicators about animal intentions, perhaps even revealing

their emotional state (more generally addressed by (Darwin 1872/1998)). The success of perception of

these patterns is therefore intimately coupled with the ability to construct internal model representations

whose assumptions and constraints reflect the proper structure and regularities present in the motions. In other words, fundamental to perception is the notion that there is indeed structure in the world that transfers to the visual image (similar to ecological optics of (Gibson 1961)). Hence the recognition of *motion categories* can be highly reliable. As for humans, some of our most basic forms of communication and expression include these same motion patterns, such as the simple repetitive nodding and swaying of the head and hands as responsive gestures (see (Davis and Bobick 1997) for an artificial vision system designed for recognizing additional human movements). Understanding how these categories are structured may give insight into how we, ourselves, categorize and develop our own cognitive models for patterns of motion in nature.

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