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The Currency of Cognition: Assessing Tools, Techniques, and Media for Complex Behavioral Analysis

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Abstract

Since 1985, long-term underwater observations of 220 Atlantic spotted dolphins (*Stenella frontalis*) and 200 bottlenose dolphins (*Tursiops truncatus*), have provided a unique opportunity to observe the flow of information within and between these societies in the clear waters of the Bahamas. Spotted dolphins are of known gender, relationships (mother/calf, siblings), and association patterns, thus providing a rich social relationship framework. In addition, human researchers enter into interactions with dolphins, providing flow of information between humans and these two delphinid species. Underwater video with hydrophone input has been used to capture contextually sensitive information, including associated vocalizations and behaviors (e.g., foraging, aggression, courtship, and discipline) with known individuals. These specific actions (e.g., gestures, vocalizations, gaze, body/head orientation, etc.) represent the potential media of information, or currency of cognition, available to dolphins. Such media are real-world, observable, and measurable signals through detailed behavioral analysis (i.e., Microethology). By measuring this flow of information in context, in real-time interactions, and through changes over time, we may be able to assess the potential for distributed cognition in this social species. Issues such as gender, age, social relations, and developmental aspects will be brought into context for applying distributed cognition analysis techniques to dolphins in ecologically valid ways.

Key Words: Dolphin, communication, distributed cognition, social learning, behavior, acoustics

Introduction

Long-term, continuous observations of the socially complex behavior of aquatic mammals have been a challenge. There are currently a few field sites around the world that have yielded (or have the potential to yield) long-term data sets capable of illuminating social learning processes (Australia – *Tursiops truncatus* [e.g., Connor et al., 1992]; Pacific Northwest – *Orcinus orca* [e.g., Ford, 1989]; Bahamas – *Stenella frontalis* [e.g., Herzing, 1997]; Hawaii – *S. longirostris* [e.g., Karczmarski et al., 2005]; Honduras – *Steno bredanensis* [Kuczaj, pers. comm.]; open ocean – *Physeter macrocephalus* [e.g., Whitehead et al., 2000]). In most free-ranging situations, we still lack the ability to observe the "process" or the "how" of social learning in wild cetaceans and how information flows between individuals. With regular access to animals and with new technological advances in underwater recording systems, such behavioral information should be forthcoming.

It has long been thought that dolphin communication is both complex and contextual (Herman & Tavolga, 1980; Tavolga, 1983; Johnson, 1993). Dolphins communicate using both vocal and nonvocal signals (Würsig et al., 1990). Qualitative descriptions of behavior and associated vocalizations of captive dolphins were reported in earlier years (Caldwell et al., 1962; Caldwell & Caldwell, 1967), Although there has been progress understanding the acoustic behavior of many species of dolphins and whales (Tyack, 1993), associating vocalizations with underwater behavior has proved difficult due to the lack of regular underwater access to dolphins and life history, sex, and relationship information. Recently, specific behavioral contexts (Dawson, 1991; Simila & Ugarte, 1993; Connor & Smolker, 1996) or behavior during regular underwater observations (Herzing, 1996) have been reported.

Although the physical structures of acoustic signals have been explored, the potential complex pattern of acoustic and postural information has yet to be deciphered in any detail. Types of social learning mechanisms (e.g., imitation, local enhancement, etc.) and the direction of information flow (vertical – mother/offspring, horizontal – peer/peer, oblique – non-parental/juvenile) have been discussed (Herzing, 2005). Empirical analysis is still lacking, however. Contextual and audience information has also been proposed as critical to the assessment of complex animal behavior (Smith, 1977). A social envelope of information might constitute the total environment that animals have available in their immediate social setting. In the case of dolphins, it might include the context and historical knowledge, including their shared history with individuals, their family, and their society. Included within this envelope is the media, or currency, of information available to dolphins such as postural, vocal, and chemical signals.

In the Bahamas, a resident group of Atlantic spotted dolphins (*Stenella frontalis*) have been behaviorally observed underwater since 1985. Life history (Herzing, 1997), correlations with sound and behavior (Herzing, 1996), and interspecific interactions (Herzing & Johnson, 1997) have been described. Because of the clarity of the water and the regular access to the 220 resident individuals, this field site provides a unique opportunity to observe complex behavior in the wild. A broad review of sound and behavioral observations of spotted dolphins is provided in Herzing (2000).

Because spotted dolphin society is conducive to complex social structure and information exchange, this paper will look at examples of underwater behavior as a model to explore ways of measuring and interpreting information flow. This work is situated in specific behavioral contexts that are observable, measurable phenomena. Primary data include communication signals (acoustic and postural) from underwater videotapes of individuals of known age and gender interacting with one another. These measurable behaviors constitute the "media" that may flow between individuals. Distributed cognition suggests that cognition occurs not just within an individual mind, but also between individuals (Smith, 1977; Tyack, 1993; Johnson, 2001). Because interactions between individuals can be recorded (e.g., behavior), they become measurable phenomena, unlike mental states and concepts like "intention" that are difficult to assess. Micro-ethology, or the detailed analysis of behavior in context, is the area of focus for this paper. We will first review what we know of Atlantic spotted dolphins' communication signals in context, then look at these signals as the potential media of information available to dolphins for exchange and shared cognitive experiences. We will then explore some tools and techniques available for the measurement of these behaviors using real examples of underwater behavioral sequences. These examples are put forth to explore ways that we might begin to measure and assess such information and media flow in a complex, cognizant system.

Materials and Methods

Study Site – Northern Bahamas

Since 1985, Atlantic spotted dolphins have been observed every summer for approximately 100 d on the NW Little Bahama Bank. This is an area of shallow water, ranging approximately 6 to 16 m in depth, 450 km^2 in size, that lies north of Grand Bahama Island. Underwater visibility averages 30 m. Observations are conducted using a 20-m motor-powered catamaran. The life history, reproductive activity, association patterns, and underwater sound and behavior of these resident dolphins have been documented for over 22 years, spanning three generations (see Herzing, 2000, for review).

Researchers regularly enter the water to obtain underwater video and simultaneous sound using various cameras (Sony TRV PC110, Yashica KXV1u Hi8 mm) with attached hydrophones. Sampling includes *ad libitum*, focal, and behavioral events (Altmann, 1974). All dolphins have been identified by sex through underwater visual observation of the genital area. Other data recorded include date, time, location, association of other individuals, and environmental information. Video information is logged and reviewed every evening on board the research vessel. A long-term data set of audio and visual information has been archived since 1985 and is accessible for detailed analysis based on individuals (220 spotted dolphins, 200 bottlenose dolphins), age classes, and behavior categories (e.g., aggression, courtship, etc). An ethogram of underwater behavioral events is coded and used (Herzing, unpub. manuscript) in *The Observer 5.0* (Noldus technologies) for in-depth behavioral analysis.

Existing Knowledge of Communication Signals as Potential Media

The total sensory envelope of potential information available for dolphins may include vocal as well as nonvocal signals such as visual, tactile, kinesthetic, and chemoreceptive signals. We know some basics of sound and behavioral correlations from this spotted dolphin community as well as from other field studies (see Caldwell et al., 1990; Smolker et al., 1993; Herzing, 1996, 2000, 2005; and Lammers et al., 2003, for more extensive discussion).

Frequency-Modulated Whistles—Such whistles are the predominant vocalizations during mother/calf reunions, helping to maintain or initiate contact between individuals.

Excitement Vocalization—*S. frontalis* produce an "excitement vocalization," a combination burst-pulsed sound, and signature whistles during behavioral contexts of alarm and distress.

Sharp Clicks—Clicks with rapid onset times, including nonvocal sounds such as tail slaps and even camera clicks from researchers, elicit startle responses in *S. frontalis*.

Buzzes—During courtship, discipline of conspecifics, or the pursuit/herding of sharks, the predominant vocalization produced is the "buzz" or "genital buzz." This vocalization is a low frequency, high-repetition rate echolocation train that is directed towards the genital or mid-section of a conspecific, often by a male to a receptive female during courtship behavior.

Aggressive Acoustics—The predominant vocalizations produced during agonistic or aggressive behavior are burst-pulsed sounds. Squawks, barks, and screams are by far the dominant vocalization during head-to-head confrontations, body charges, and open-mouth posturing.

Synchronized Squawks—Dolphins produce synchronized squawks during synchronized physical activity in highly escalated aggressive activity, intra- and interspecifically. Adult male *S. frontalis* coordinate their swimming behavior, postures, and squawks. Young juvenile males show partial synchronization of swimming behavior and squawks but are not fully coordinated in their efforts.

Echolocation—Echolocation click trains with terminal buzzes are predominant vocalizations produced during hunting and foraging behavior.

Nonvocal Acoustics—Nonvocal acoustics that are associated with behavioral activity are also observed during underwater observations, including (1) tail slaps – as attention-getting mechanisms or in annoyance; (2) jaw claps – in escalated aggression; (3) aerial displays – during play behavior and also during intra- and interspecific aggressive chases; (4) bubble displays – in the production of whistles (bubble trails), in annoyance (full and half bubbles), and during annoyance or aggressive contexts (torus bubble rings); and (5) in-air vocalizations, including the chuff (an explosive exhalation) during annoyance and raspberry (a constricted exhalation) in interspecies' affiliative contexts.

Nonvocal Impulse Sounds—These sounds are produced by the slamming of body parts, cavitational movements, percussive thrashing during attempted hits, closure of the jaw, and various aerial behaviors.

Problem Areas for Communication Signal Analysis

Before we can take a close look at shared cognition through micro-behavioral analysis, there are a few critical gaps in our signal acquisition that we need to improve.

Full Broadband Acoustic Signals—Although many vocalizations under analysis are within human audible range, only recently have tools and techniques been developed to correlate full bandwidth sound recordings with underwater behavior (Lammers et al., 2003). Bandwidth-limited technology has been the largest obstacle in obtaining full sound production information, and our inability to regularly document the high-frequency information available to social species greatly hinders us from observing the full spectrum of information.

Sound Units and Categories—The identification and isolation of individual structural units of sound within the dolphin signal repertoire have not been adequately studied. Increased understanding of mechanistic and perceptual classification is needed to determine the natural boundaries of signal classification by delphinids, as it has been for other taxa (Marler, 1982; May et al., 1989; Ehret, 1992) and with vervet monkeys (Seyfarth & Cheney, 1980; Seyfarth et al., 1980).

Determining relevant units of analysis in communication systems involves choosing between multiple parameters, such as duration, amplitude, and frequency, of both acoustic and other modality signals. Spacing between signals and sequential or combinatorial units may be equally important to measure as the individual signals itself. Such signal relations have been discussed on theoretical grounds (Johnson, 1993) but should be incorporated into analysis techniques.

Media Flow and Interpretation by Receiver—The relative positioning of conspecifics during signal production may be critical in the analysis of shared cognitive information. Close proximity and angle are crucial in determining the eavesdropping abilities of *T. truncatus* (Xitco & Roitblat, 1996). States of joint attention and shared coordination may be key to the synchrony of behavior for mutual goals in dolphins, including shared attention and referential pointing (Xitco et al., 2004). Determining the directionality of social sounds (e.g., burst-pulsed and whistles) as well as the directionality and use of dolphin echolocation as a potential "point" for conspecifics' use would be advantageous in assessing the potential information available to dolphins.

Importance of Underwater Documentation of Behavior

The complexity of most detailed behavior requires video documentation. With a fast-moving species like dolphins, utilization of slow motion techniques and repetitive review of such behavior is critical. The acquisition of underwater data sets entails a new set of problems in the wild, including access and tolerance by the species, clear underwater viewing, and regular access and proximity. To date, there are only a few sites in the world, most of them tropical, where such data sets are emerging. Captive facilities with underwater viewing areas also will allow such opportunities for the acquisition and analysis of underwater interactions. In either scenario, when underwater video of behavior becomes possible, it is then necessary to consider the following.

Ethogram Design – Choosing Events or States as Measures

Behaviors are usually measured as either short-term events or long-term states. Events considered short duration behaviors are scored in frequencies of occurrence or sequences of events. In the dolphin literature, these are described as head to head, pec to pec rubs, etc. In human literature, we might describe waving arms, scratching our head, etc.

States of behavior considered long duration behaviors are scored as durations of activity or sequences of activity states. In the dolphin literature, these are described as resting, traveling, socializing, foraging, etc. In the human literature, they are described as approaching, departing, joint attention states, states of engagement, etc.

Results

After observing individual dolphins underwater in the Bahamas for 20 y, I can say that watching the development of different behaviors in order to compare adults to juveniles has been the most productive, and certainly invaluable, aspect of understanding the dolphins' society and communication system.

Because distributed cognition posits shared information and media flow, it is important to analyze the simultaneous tracking of multiple individuals and multiple modalities (e.g., sound, touch) as an attempt at a richer view of interaction. Taking into account the information of signal correlation reviewed above, we can look at time-series analysis of simultaneous behaviors (e.g., events or states) of multiple individuals, or focal subgroups, measuring both postural and acoustic signals in both regular and slow motion (Figures 1 & 2). We can then look at the sequence and timing of signals (e.g., within sequences, between age classes, etc.), temporal changes of behavioral events or states on different time scales, or spatial changes on different time scales.

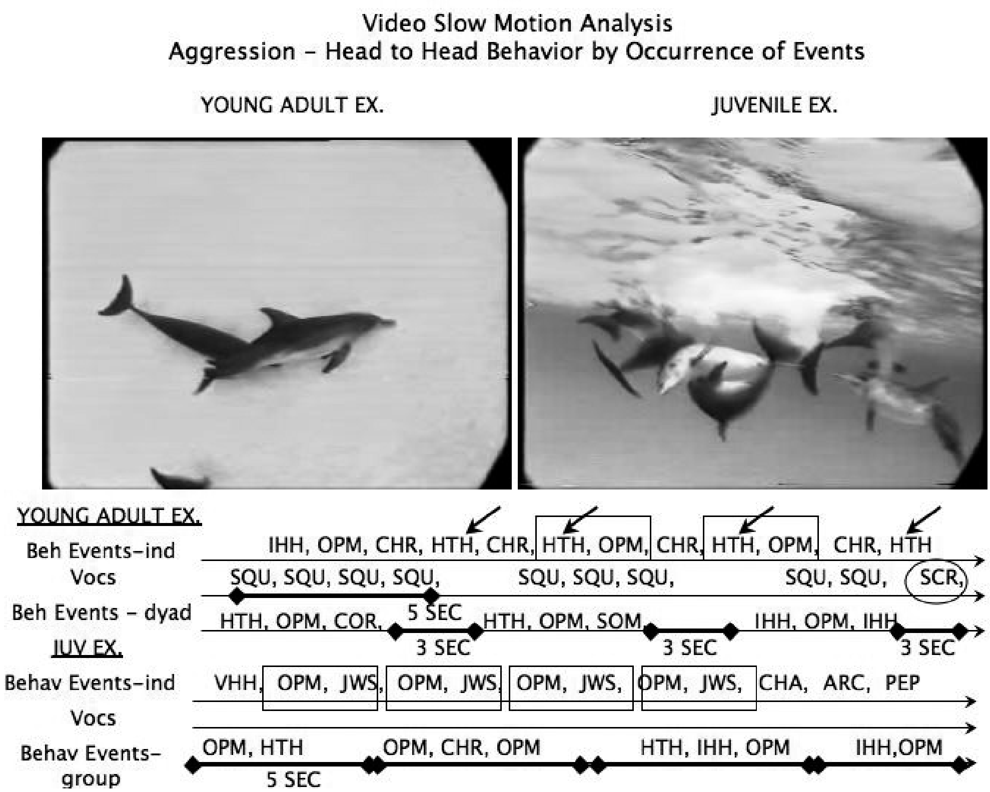

Figure 1. Three simultaneous timelines for video slow motion analysis; behavioral events are shown for aggressive postures and vocalizations for a young adult and a juvenile video clip.

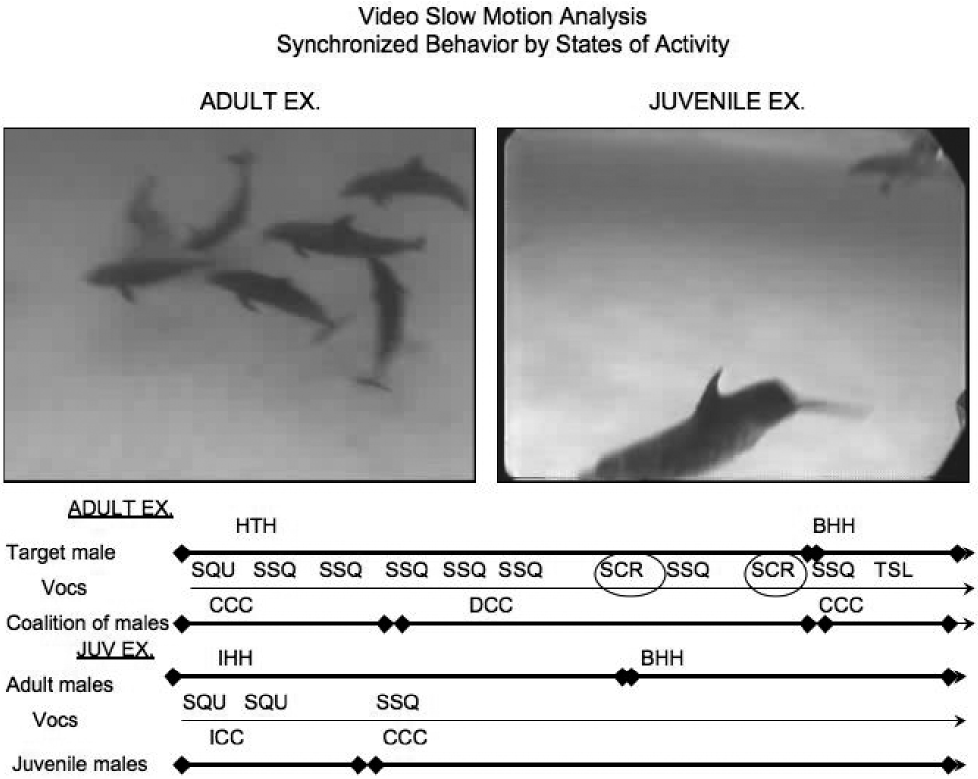

Figure 2. Three simultaneous timelines for video slow motion analysis; behavioral states are shown for synchronized postures and vocalizations for an adult and a juvenile video clip.

A Theoretical Example of Complex Behavioral Analysis – Example 1

Video Analysis: Behavioral Context: Aggression—The video analysis featured in Figure 1 is an example of typical aggressive behavior seen in fully grown adults as compared to juveniles who are still developing their fighting skills.

In this figure, we see an example of young adult behavior. In this first example, we have taken 2 min of underwater video (represented by photo), reviewed it, and measured the frequency of occurrence of behavioral events and sequential patterns of an individual vs a dyad of dolphins, with a third simultaneous timeline for vocalizations as originally coded in our ethogram (Table 1).

Behavioral Events Individual—In the first timeline, we scored the occurrences of specific postural events, including four head to heads (HTH), three open mouth postures (OPM), and four charges (CHR) within this time period. We have also scored behaviors that were clustered, or followed each other, including two times that HTH preceded OPM events by this individual. With longer time samples, we might see more clusters of events together in different sequences.

Table 1. Ethogram coding of behavioral events, states, and vocalizations for Atlantic spotted dolphin

Code	Description
IHH	Inverted head-to-head posture
OPM	Open-mouth posture
CHR	Charge
HTH	Head-to-head posture
COR	Coordinated orientation
SOM	Stationary open-mouth posture
VHH	Vertical head-to-head posture
BHH	Break head-to-head posture
JWS	Jaw snap
TWS	Tail slap
CHA	Chase
ARC	Arch
PEP	Perpendicular pass
CCC	Coalition coordinated chase
DCC	Disband coordinated chase
ICC	Independent coordinated chase
SQU	Squawk
SSQ	Synchronized squawk
SCR	Scream

Vocalizations—In the second timeline, we scored the occurrence of types of vocalizations. We see a cluster of burst-pulsed sounds squawks (SQU, SQU, . . .) followed by a break, and another cluster of SQU. Towards the end of this timeline, we scored the presence of a scream (SCR) within a cluster of SQU. We also measured the duration of these bouts of SQU. On its own, this timeline is interesting for its pattern of sounds; however, overlaying it with the first timeline, for example, we are able to look at when the scream occurred relative to the behavioral activity of the individual on the first timeline.

Behavioral Events Dyad—In the third timeline, we followed the activities of a dyad that are synchronized with each other and interacting with the individual scored in the first timeline. Again, we count two HTH, which are followed by OPM behavior. We can also count the spacing or time interval between these bouts of behavior.

Of course, such elementary frequency counts of behavioral events can be done easily. Using all three timelines, we may now begin to measure the coordinated timing of events. This allows us to ask complicated questions like "Does the occurrence of the SCR correlate with any specific events of either the individual or dyad of dolphins?" This is the power of simultaneous and multimodal analysis.

Figure 1 also contains a juvenile example of aggression. We have measured the same types of postures over simultaneous time scales between an individual and a dyad. We can see that the placement of OPM now precedes the Jaw Snap (JWS), differing from the adult sequence of behavior. Also, JWS are more frequently seen in this example of juvenile aggression than in the adult video. Again, basic frequency counts of behavior are fairly standard, but one striking feature of the immediate difference between the juvenile video sequence and the young adult video sequence is the lack of any vocalizations scored during juvenile aggression. This gives us the potential to look at multifaceted aspects of shared cognitive events across developmental periods; however, it may occur in similar behavioral contexts as well, but it may differ in temporal space and content.

A Theoretical Example of Complex Behavioral Analysis – Example 2

Video Analysis: Behavioral Context: Synchronized Chases—The video analysis featured in Figure 2 is an example of synchronized behavior that occurs in male coalitions. In the adult video, a dyad of adult dolphins is targeting another adult male dolphin. In the juvenile example, there is a mock fight and attempted coordination by juvenile males against adult males.

In Figure 2, we look at the simultaneous timelines of an adult male dolphin vs a dyad, as well as a timeline for vocalizations. In this case, we scored states of behavior such as coordinated chases (CCC) and coordinated orientation (COR).

Target Male—In the first timeline, we scored the duration of the state of being in a HTH. The dolphins Break Head to Head (BHH) following the first state.

Vocalizations—In the second timeline, we scored vocal activity. On this timeline, we can see that a change of state of SQU is disrupted twice by SCR, one of which occurs right before the target male BHH (seen in the first timeline).

Coalition of Males—In the third timeline, we scored the duration of the state of Coalition Coordinated Chase (CCC), followed by a Disband Coordinated Chase (DCC), followed again by a CCC, which is also synchronized with the BHH of the target male in the first timeline.

In Figure 2, we scored the activities of juvenile vs adult dolphins and have three simultaneous timelines for analysis.

Adult Males—In this first timeline, we scored the adult males in their states of Inverted Head to Head (IHH), followed by BHH.

Vocalizations—In this second timeline, we scored the state of SQU followed by a state of Synchronized Squawks (SSQ). Again, durations for these states can be measured.

Juvenile Males—In this third timeline, we scored the duration of the first state of Independent Coordinated Chases (ICC), followed by a CCC.

Although behaviors and vocalizations are interesting within their own timelines (i.e., duration of behavioral state), it is even more interesting, and perhaps more to the point, to view the three simultaneous timelines and their relations and timing. Since micro-ethology measures the interaction between individuals, it is these shared activities and their synchronous or sequential relations that may lend insight about what shared cognitive information flows between dolphins. The simultaneous measurements of multiple modalities with multiple individuals or groups allows us to view the timing and access to signals and information in a larger, social context. The analysis of dynamics and systems of such interactions then becomes possible.

Discussion

Although traditional behavioral sampling is often used in the study of delphinid communication (Altmann, 1974; Slooten, 1994), a neglected area of analysis is in the rhythmic and sequential aspects of behavior and acoustics (van Hooff, 1982; dos Santos et al., 1995). Signal relations in a sequence of action may also be worthy of exploration. For example, the relative amplitude in a call, the intensity or rate of a postural movement, can add information to a sequence of events critical for the receiver to interpret. The frequency of a signal, the rhythm, silent pauses, differences in parameter in terms of frequency or amplitude modulation, and the sequential escalation of signals are higher-level communicative features for accessing both social negotiation and passive informational content. The recognition of rhythmic components in dolphin communication has been documented by Lilly (1965) and Gish (1979) and more recently by Richards et al. (1984) and Xitco (1998). The recent studies refer to specific mimicry of space between both signals and the initiation of signals. Sequential analysis has been used in human communication and yields both time-dependent (rhythm) and time-independent (grammar/order) aspects of communication combined into innovative pattern recognition programs (Magnusson, 1996, 2000). Sequential analysis means that the order and temporal integrity of signals are conserved in space and time. This will require the simultaneous timelines and subgroup analysis proposed here.

Shared cognitive environments have special relevance for sharing communication and negotiating—especially in sympatric species (Smuts et al., 1987; Herzing & Johnson, 1997). Mutual cognitive environments between species are likely to produce pressures for shared interspecific communication. Many species utilize acoustic information from neighboring species (Fagan, 1981) and in referential communication (Struhsaker, 1967). Human/nonhuman species interaction has been documented with domestic dogs (McConnell, 1990), in human/dolphin cooperative fisheries (Pryor et al., 1990), in sentinel species that give alarm calls to warn mixed species aggregations of approaching predators (Munn, 1986), and in chimpanzee studies in which potential enculturation issues have arisen (Bjorklund et al., 2002). It is these issues that support the notion that cognition is potentially shared within the group as well as between taxa. Such information may be a shared cognitive experience based on shared physical cross-taxa attributes as described by Morton (1977) or shared cross-modal features (Pack & Herman, 1995).

Difficulties and Potential Solutions to Studying Cognition in Observational Settings

Know Your Players—Photo identification has been a mainstay in the study of many mammalian populations. Knowing the individual animals, their gender, reproductive history, and their relationship to each other will be critical to the understanding of social cognition. The emerging area of personality studies for many taxa suggests that individual tendencies must be considered and assessed in any behavioral study.

Know the Sensory World and Communication Repertoire for Your Players—We will need to get into the *Umwelt* of our study individuals as much as possible. This may involve working in a captive situation and knowing a few individuals over the long term, or working in a free-ranging situation and knowing individuals within a normal societal context but with limited exposure.

Know Comparative Work—Primate and most terrestrial researchers have had much better access to their study animals, either in animal parks or nature, and have been able to get some observation time under their belts. We don't really need to reinvent the wheel. Perhaps we just need to modify the wheel a bit for the aquatic environment and stay up-to-date on new methods and tools used in other disciplines and with other taxa.

Some Suggested Tools in the Study of Cognition in Marine Mammals

Observational Tools – Study Sites and Locations—Finding a study site—either a marine park that can commit long-term to research or a location that you can commit to that has good and regular access to animals—is paramount.

Archival Tools—Although our eyes and paper data collection may suffice in some situations, building a long-term, archived, and coded video data set in multiple modalities (e.g., visual, sound, etc.) can enhance our abilities to capture and observe, in slow, medium, or fast motion, the complex behavior of these animals.

Here I can speak from quite personal experience as my own long-term project has yielded a complex and well-tracked underwater data set. With this data set, students can gather observational data from the video library and ask complicated behavioral questions over large temporal scales, and, in this case, long developmental time frames. This is no different than any other long-term data set as far as complex information, except that it is preserved, real-time behavior that can be analyzed and re-analyzed in various temporal and spatial scales with multiple channels of information.

Analysis Tools

The Observer (Behavioral Software)—This behavioral software, developed by Noldus Technologies, allows the behavioral observer to code, observe, and analyze complex behavior (live or video segments). This program also does elementary statistics and, with additional modules, can do higher-level nested analysis (Magnusson, 2000).

Video Analysis—The use of slow motion, fast motion, and coordinated analysis of sounds and behavior can be invaluable in the data collection of complex interactions. Preserving sequential information may be particularly helpful for these cognitive questions and analysis.

Systems State Analysis—The application of systems state analysis techniques has been explored in baboons for potential comparative methodology (Forster, 2002). Such approaches are novel and innovated, and may provide insight into yet unforeseen relationships and transitions of behavioral dynamics.

To discover the link between social and cognitive complexity, we will need to look at sequential or cumulative effects of multiple mechanisms and sensory systems at work simultaneously and over time to fully understand the process of social learning. One way to do this might be to look at the potential constraints of information. What are information transmission inhibitors and the constraints of social learning and information flow? How is information reduced, or when do senses fail? Is there a lack of experience by tutors or models? Do dominant individuals hog opportunities, providing a lack of experience for other less dominant individuals? These sorts of questions will help us probe the complex nature of sharing cognitive information.

To solve the challenges of current fieldwork constraints, and there are a few yet unresolved, we need to deal with (1) ultrasound as additional signal information available and for the categorization of sound types; (2) the localization of the producer of information; and (3) the inclusion of multiple sensory modalities for interpretation, specifically chemoreception and kinesthetic/rotational information as media.

The development of these methodological tools should eventually yield parallel and comparative tools, measures, and definitions for cross-species/taxa comparisons. Thinking in broader terms of what kinds of information may be available to dolphins (e.g., symbolic, referential) and how it flows between individuals may help us open up new areas of exploration in the cognitive world of marine mammals.

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