Monkey Semantics:
Two 'Dialects' of Campbell's Monkey Alarm Calls*

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Abstract. We develop a formal semantic analysis of the alarm calls used by Campbell's monkeys in the Tai forest (Ivory Coast) and on Tiwai island (Sierra Leone) – two sites that differ in the main predators that the monkeys are exposed to (eagles on Tiwai vs. eagles and leopards in Tai). Building on data discussed in Ouattara et al. 2009a,b and Arnold et al. 2013, we argue that on both sites alarm calls include the roots *krak, hok, wak,* which can optionally be affixed with *-oo*, a kind of attenuating suffix; in addition, sentences can start with *boom boom,* which indicates that the context is not one of predation. In line with Arnold et al. 2013, we show that the meaning of the roots is not quite the same in Tai and on Tiwai: *krak* often functions as a leopard alarm call in Tai, but as a general alarm call on Tiwai. We develop models based on a compositional semantics in which concatenation is interpreted as conjunction, roots have lexical meanings, *-oo* is an attenuating suffix, and an all-purpose alarm parameter is raised with each individual call. The first model accounts for the difference between Tai and Tiwai by way of different lexical entries for *krak*. The second model gives the same underspecified entry to *krak* in both locations (= general alarm call), but it makes use of a competition mechanism akin to scalar implicatures. In Tai, strengthening yields a meaning equivalent to *non-aerial dangerous predator* and turns out to single out leopards. On Tiwai, strengthening yields a nearly contradictory meaning due to the absence of ground predators, and only the unstrengthened meaning is used.

Keywords: primate linguistics, primate semantics, alarm calls, primate communication

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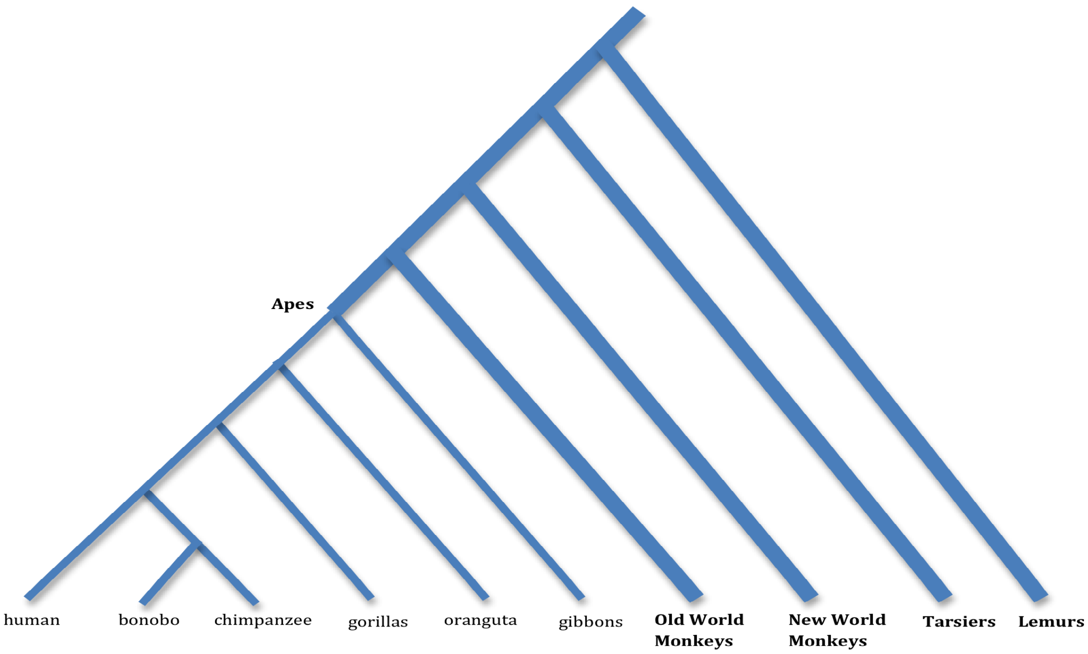
We develop a formal semantic analysis of the alarm calls of male Campbell's monkeys, a species of Old World monkeys (specifically, of cercopitheci) which is doubly interesting for linguists. First, as shown in detail by Ouattara et al. 2009a, b, these alarm calls appear to include meaningful roots, a suffix, and possibly a non-trivial syntax. Second, as investigated by Arnold et al. 2013, environmental differences give rise to an apparent dialectal difference between the call systems found at two sites, the Tai forest in Ivory Coast, and Tiwai island in Sierra Leone (they primarily differ in that leopards are present in Tai and absent from Tiwai). We sketch and compare two models of the commonalities and differences between these call systems. One model posits a real dialectal difference in the meaning of one call, *krak*, used as a leopard alarm in Tai but as a general alarm on Tiwai. The other model assigns a single, innate meaning of general alarm to *krak*, but relies on a rule of strengthening – akin to scalar implicatures – to derive a 'ground predator' meaning; for lack of such predators on Tiwai, the rule simply fails to be applied. In this second analysis, we don't have different dialects in a technical sense, but the underlying semantic system is far more complex than is standardly expected for monkey calls.

In what follows, we freely apply linguistic terminology to these calls, with the belief that they can and should be studied as formal languages with a sound system, a lexicon, a morphology, a syntax, a semantics, and a pragmatics. Importantly, we do not take a stand on the relation that these systems bear to human language; to say that they can be studied as formal systems does not imply that they share non-trivial properties with human language, nor that they share an evolutionary origin with it. In fact, call systems that have properties reminiscent of those we study here were described in Madagascar lemurs, which are phylogenetically extremely distant from Campbells's monkeys, and also from humans, as seen in (1) (their most recent common ancestor with either species lived approximately 69 million years ago (Perelman et al. 2010); for comparison, humans and chimpanzees have a most recent ancestor that lived approximately 6-7 million years ago, while humans and Campbell's monkeys have a most recent common ancestor that lived 20-38 million years ago). We do believe, however, that any comparison between human language and alarm calls will be illuminated by a precise formal analysis of the latter.

(1) Primate phylogeny



One cautionary note is in order before we start. In a strict sense, a *semantic rule* requires relatively little: a relation of denotation or satisfaction between primitive objects of a (usually discrete) system and parts of the world (e.g. objects or situations); and a way to extend this relation to a language obtained by combining these primitive objects into sequences. If the final relation is based on truth (yielding statements such as *situation w satisfies sentence S if and only if* ____), one can further posit that users of this system may have at their disposal a relation of entailment, with the condition that *sentence S entails sentence S' if and only if every situation that makes S true makes S' true*. Nothing in the definition of a semantic rule, or even of entailment, requires a high degree of rationality, let alone a theory of mind. In fact, even parts of *pragmatics* can be developed with relatively little machinery. For instance, in their simplest version scalar implicatures only require that subjects have at their disposal (i) a notion of satisfaction (to determine whether a sentence *S* – e.g. *p or q* – is compatible with the situation at hand); (ii) a notion of scalar alternatives (to determine whether the sentence *S'* (e.g. *p and q*) competes with the sentence *S*); and (iii) a notion of entailment (to determine whether *S'* is more informative than *S*). These three ingredients could suffice to yield the inference that if *p or q* was uttered, the more informative statement *p and q* is false. When one considers other parts of pragmatics, such as presupposition theory, things might be rather different. Presuppositions are often analyzed in terms of common belief (e.g. Stalnaker 2002). If so, in order to determine whether a presupposition is or isn't satisfied, one needs to determine whether it is compatible with what is common belief in the conversation, which presumably requires an ability to represent another person's beliefs, and to compute complex notions on that basis. Importantly, in the present piece *we will only use tools from elementary semantics and (in our second model) of simple implicature theory*. Thus even if the most sophisticated of our models is correct, this piece will have few implications about the reasoning abilities of Campbell's monkeys.

1 Introduction to Call Semantics

1.1 General Issues

Like many other mammals and birds, some primates produce vocalizations when exposed to predators (as well as to other disturbances). From a semantic perspective, these raise several questions.

(i) *Function:* Do the calls communicate informational content to conspecifics? Often, calls have a dual function: to alert – and thus communicate information to – conspecifics, but also to deter a predator, for instance by letting it know that it has been detected (e.g. Caro 2005).

(ii) *Content:* When calls communicate information to conspecifics, what is their semantic content? One important distinction is whether calls directly encode information about a predator type, or information about properties of the threat (level, directional origin, etc), or a combination of both. In the first case (information about predator types), ethologists often say that the calls are 'referential'[1].

Summarizing recent research, Cäsar et al. 2012 write:

"... it is not clear whether primates intend to produce calls that refer to specific external events, or whether they merely respond to "evolutionarily important" events that place them into different motivations. One way to address this has been by investigating whether associated variables, such as the level of threat experienced by the caller, can explain the caller's behaviour better than the predatory category (e.g., California ground squirrels: Owings and Virginia 1978). In some other species, it has been argued that alarm calls refer to both the level and type of threat (Manser et al. 2002; Templeton et al. 2005; Sieving et al. 2010). Chickadees (Poecile atricapilla), for instance, produce "seet" alarm call in response to flying raptors and a "chick-a-dee" alarm call in response to perched or stationary raptors, but their calls also provide information about the threat level (Templeton et al. 2005). Within the primate lineage, the predator type appears to have an overriding influence on alarm calling behaviour, with little evidence that variation in distance or direction has a major impact (e.g., vervet monkeys:

[1] This need not imply that such calls are referential in the semanticist's sense, i.e. that that they are 'expressions of type e' within a type-theoretic system. In fact, given that calls appear to convey information on their own, it is rather natural to give them a propositional semantics (= 'type t') – which is the line we will take in our analysis of Campbell calls.

Cheney and Seyfarth 1990, Diana monkeys: Zuberbühler 2000b)."

(iii) *Organization:* What is it in calls that carries information to conspecifics (when such information is conveyed)? As Cäsar et al. 2012 write in their initial summary:

"some species produce **several acoustically distinct alarm calls** in response to different predator types (Seyfarth et al. 1980a, b; Manser et al. 2002; Templeton et al. 2005), but in others, the nature of the danger encountered is reflected by the **number of calls** per sequence (Schel et al. 2009), the **rate of call delivery** (Lemasson et al. 2010), the **intensity of calls** (Blumstein 1999), or by combinations of calls (Arnold and Zuberbühler 2006a, b)."

As with other semantic systems, it is natural to ask which *lexical meanings* (if any) are available at the level of individual calls, and then what are the *rules of combination* by which sequences can be interpreted (if indeed these sequences have a compositional-like structure; otherwise, meanings for entire sequences might have to be stored as if they were lexical meanings).

(iv) *Development and variation:* How do the form and meaning of calls develop, both at the level of individual calls and of sequences? While some aspects of calls might be innate, some might have to be acquired. Among the latter, it would be particularly interesting to determine whether different groups of the same biological species can display dialectal differences in terms of forms, meanings, or both.

Before we come to Campbell's monkeys, it will be helpful to see how some of these questions were addressed for other primate species. In the rest of this introduction, we summarize some results that will bear on the present study. In a nutshell:
–Seyfarth et al.'s pioneering study (1980a, b) of alarm calls in vervet monkeys defined the main questions and established the methodology, based on field experiments (see also Struhsaker 1967). They showed that vervet monkeys have different calls for eagles, snakes and leopards, and studied the ontogenetic development of these calls.
–Fichtel and Kappeler 2002 showed that two species of Madagascar lemurs have a call system that has (i) a specific alarm call for aerial predators, and (ii) a general-purpose alarm call for ground threats. Despite the phylogenetic distance between lemurs and cercopitheci, in our final analysis of Campbell calls we will come to a rather similar conclusion, with a specific raptor alarm call and a general alarm call – a pattern which, according to Wheeler and Fischer 2012, is found across several primate species.
–Stephan and Zuberbühler 2008 studied another family of cercopitheci, Diana monkeys, which also exist in the Tai forest and on Tiwai island, and are relatively closely related to Campbell's monkeys. They showed that sequence length (i) could carry information about the threats, and (ii) sometimes differed across Tiwai and Tai; but they did not claim that this was a *bona fide* dialectal difference.
–Arnold and Zuberbühler 2008, 2012 studied the calls of putty-nosed monkeys (a species of cercopitheci less closely related to Campbell's monkeys than Diana monkeys are), and concluded that they use call combinations to convey information that is distinct from that of the individual calls. Importantly, they found no evidence of a compositional system, and argued instead that complex calls should be analyzed as some kinds of 'idioms'.

1.2 Vervet Monkeys and 'referential' calls Seyfarth et al. 1980a, b

In their pioneering study of monkey alarm calls, Seyfarth et al. 1980a, b showed that vervet monkeys use three alarm calls that carry information about the presence of eagles, snakes and leopards respectively; they investigated both the production of these calls when different threats naturally arise, and they assessed the monkeys' reactions by way of playback experiments. They further investigated the *development* of these calls from infants to adults, and showed that "as infants grow older they sharpen the association between predator species and the type of alarm call" (the developement of this call system was investigated in greater detail in Seyfarth and Cheney 1986); the more discrimating calling behavior of adults compared to juveniles and infants is depicted in (2).

(2) Seyfarth et al. 1980a on the development of vervet monkey calling behavior

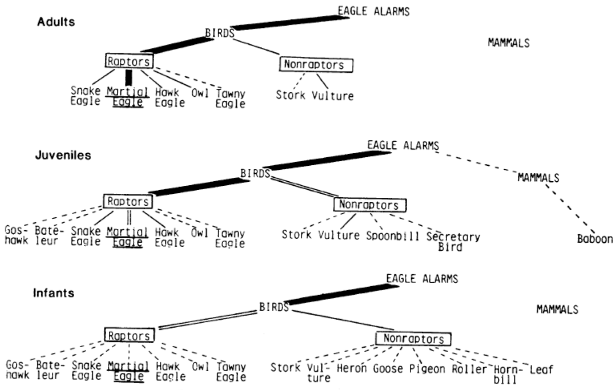


Fig. 1. Eagle alarms given by adult, juvenile, and infant monkeys to different species or objects. Broken line, 1 to 5 alarms; single line, 6 to 10 alarms; double line, 11 to 15 alarms; solid line, more than 15 alarms. Data on 149 alarms were collected over 14 months from 31 adults, 16 juveniles, and 17 infants.

Importantly, Seyfarth et al. 1980a, b did not decisively distinguish between two possible interpretations of their data. One involves *semantic development,* in the sense that vervet monkeys gradually acquire a more refined meaning for the relevant alarm calls as they get more exposure to their environment – which in principle might allow for dialectal variation as well (none was displayed in adult vervet monkeys). An alternative interpretation pertains to *pragmatic development* instead: the meaning of the calls might remain constant throughout the vervet monkey's life, but as a monkey becomes more mature it might learn than only some events are worth talking about. On this view, what the researchers labeled as an 'eagle' alarm call might in fact be a bird alarm call (as in the infants' use); but as they grow older, the monkeys might gradually realize that only dangerous birds are worth calling to.

A further issue, which will matter in the present study, is whether the development of the call system of vervet monkeys involves learning. Seyfarth and Cheney 1986 emphasize that they do not have *conclusive* evidence that it does, but they provide suggestive arguments. As they write, "after an infant has given an eagle alarm call to a genuine predator, adults are significantly more likely to alarm-call themselves than when the infant alarm-calls at a non-predator" – which might suggest that there exists a mechanism of positive reinforcement; and similarly, "when infants respond to the playback of an alarm call, they are significantly more likely to do so correctly if they have first looked at an adult". Importantly, even if learning is involved, these observations do not help decide whether it is of a semantic or of a pragmatic nature.

1.3 General vs. predator-specific calls (Wheeler and Fischer 2012, Fichtel and Kappeler 2002)

While alarm calls are found across primate species, Wheeler and Fischer 2012 note an interesting trend that will be of some import in our final analysis of Campbell's monkey calls. As they write, "across species it tends to be the call associated with terrestrial predators that is given in other contexts, whereas the call associated with aerial predators tends to be context-specific ... "; they cite examples from capuchin monkeys (New World monkeys), tamarins (New World monkeys), and lemurs. Two species of the latter were investigated in Fichtel and Kappeler 2002: redfronted lemurs (Eulemur fulvus rufus) and white sifakas (Propithecus verreauxi verreauxi). Fichtel and Kappeler found that "both species gave specific alarm calls only in response to raptor playbacks and the corresponding alarm calls, whereas calls given in response to carnivores and the corresponding alarm calls were also observed in other situations characterized by high arousal". Thus it appears that the two calls found in lemurs do not play symmetric roles: one is specifically related to eagles, whereas the other call seems to be one of general alarm. Initially, the data from Campbell's monkeys appear to be quite different: in data from the Tai forest, the leopard call and the eagle call appear to play symmetric roles; but in our final analysis, we will argue that the leopard call is in fact a general alarm call, which falls under the broad generalization discussed by Wheeler and Fischer and illustrated in lemurs.

1.4 Diana monkeys, sequence length and dialectal variation (Stephan and Zuberbühler 2008)

It has been noted for several monkey species that the number of calls per series, or the call rate, seem to carry meaning (in fact, call rate appears to carry information in Campbell's monkeys, a point to which we return below). Stephan and Zuberbühler 2008 study a difference in calling behavior between male Diana monkeys of the Tai forest (Ivory Coast) and their male cousins from Tiwai island (Sierra Leone). In Tai, Diana monkeys have two primary predators besides humans and chimpanzees: leopards and crowned eagles. By contrast, on Tiwai islands "leopards have not been reported for at least 30 years" (Stephan and Zuberbühler 2008), hence since the late 1970's – which leaves crowned eagles as the main predator.[2]

Stephan and Zuberbühler studied the calling behavior of male Diana monkeys of the two sites in field experiments in which they played (i) Diana eagle calls (= DE); (ii) Diana leopard calls (= DL); (iii) eagle shrieks (= E); (iv) leopard growls (= L).

(3) Differential calling behavior of Diana monkeys in the Tai forest and on Tiwai island

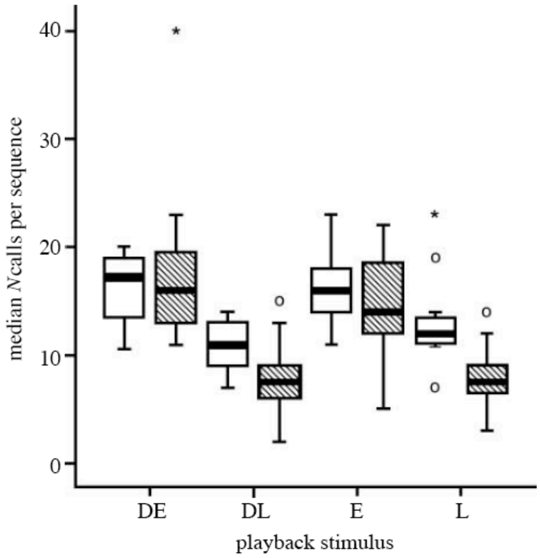


Figure 2. Median numbers of calls per sequence of Taï (hatched boxes) and Tiwai (open boxes) Diana monkeys to playbacks of eagle shrieks (E), leopard growls (L), male Diana alarm calls to eagles (DE) and male Diana alarm calls to leopards (DL). Box plots show median values, quartiles, range and outliers. Circles and asterisks show extreme values, asterisks being more extreme.

As shown in (3), the median numbers of calls were approximately the same across the two sites in eagle-related situations. But in leopard-related situations, this was not so. Crucially, the authors found that "at Tai, males discriminate acoustically between their responses to leopards and general disturbances, such as falling trees or fleeing duikers (Zuberbühler et al. 1997), whereas at Tiwai, males also responded regularly to such general disturbances, but these call sequences were not different from the ones given to leopard-related stimuli (...)".[3]

Importantly, these findings can be interpreted in two ways. First, there could be a *difference in the meaning* of the length of call sequences – and thus a difference in the (ill-understood!) semantics of the relevant call systems.[4] Alternatively, it could be that the two call systems have

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[2] Humans are chimpanzees do prey on monkeys, but the latter are usually believed not to give rise to alarm calls because they are pursuit hunters, hence calling to them would only help them locate their victims.

[3] They provide the following data for Tai: Median$_{leopard}$=11 vs Median$_{unspecific}$=6, U=21.0, p=.26 and for Tiwai: Median$_{leopard}$=7 vs. Median$_{unspecific}$=6, U=15.5, p=.45. This should be compared to their figure 2, reproduced in (3) in our text.

[4] The semantics is ill-understood, among others, because it isn't clear what sequence length corresponds to. In Tai, eagles trigger longer sequences than leopards, possibly eagles are more dangerous than leopards (e.g. to

exactly the same semantics, and that the differential calling behavior across the two sites just reflects a *cognitive difference in world knowledge* on the part of the language users. This is a particularly natural interpretation because the difference observed solely concerns leopards, which are familiar to the Tai monkeys but not to their cousins from Tiwai. Thus Tiwai Diana males might call to leopard growls in the same way as to general alarms *because they just don't know what kind of threat they are*; nothing follows about the semantic properties of the call system. To have a *bona fide* argument for a semantic difference, one should display a case in which a stimulus that plausibly corresponds to the same life experience across the two sites gives rise to a differential calling behavior; we do not have this for Diana monkeys – but we will for Campbell's monkeys.

1.5 Putty-nosed monkeys and call combination

Arnold and Zuberbühler 2008, 2012 explored one interesting instance of *call combination*. They showed that putty-nosed monkeys have two elementary calls, *pyows,* which are usually given to crowned eagles, and *hacks*, which are given to leopards and other disturbances. Interestingly, alternating series of 1-4 *pyows* followed by 1-4 *hacks* are predictive of group progression. In this case, two call types can be combined to form a third one, but unlike what is usually found in human language, there is no evidence that the combination is compositional: the meaning of the alternating sequences cannot currently be derived from the individual meanings assigned to each call; if the accepted analysis of these calls is correct, we have a case of syntactic combination without semantic composition.

1.6 The importance of Campbell's monkey calls

The research summarized above has left several questions open.
(i) *Structure:* Do some systems of primate alarm calls have a non-trivial syntactic and/or semantic structure? In particular, is it possible to discern some version of a compositional system, as is found in human language – in other words, can we find cases in which different syntactic rules are associated with different ways to combine meanings?
(ii) *Variation:* Are these systems of calls entirely innate, or are they in part learned? In the latter case, is it possible to find dialectal differences in the alarm calls of different groups of the same species of primates?
(iii) *Methodology:* On a methodological level, can one construct insightful formal models of the syntax, semantics and possibly pragmatics of these alarm calls? The question is of course particularly relevant to the extent that one has found non-trivial properties that can benefit from a formal approach.

The *first question* was addressed in Ouattara et al. (2009a,b), who made two key discoveries on the alarm calls of male Campbell's monkeys (note that females have calls as well, but they are different from those of males and considerably less loud – which makes them harder to study; males start uttering 'male' alarm calls around adolescence).
–First, Campbell's monkey alarm calls have a root-suffix morphological structure: a suffix *-oo* can be added to the roots *krak, hok* and *wak* to yield *krak-oo, hok-oo,* and *wak-oo* (the root *wak* was not found on its own in the limited data they discussed, but it is in the more recent ones we discuss below).
–Second, Campbell's monkey calls involve at least one syntactic rule: a particular call, *boom*, produced by filling airsacks, is usually found at the beginning of sequences only, and is usually

escape from leopards, monkeys only need to climb on thin branches that are beyond the leopard's reach). But on Tiwai, leopards growls are apparently assimilated to general alarms, and give rise to *longer* sequences than in Tai.

reduplicated.[5] Furthermore, it seems to radically modify their meanings: a sequence that causes other monkeys to be alert to the presence of predators loses this effect when it is prefixed with *boom boom*.[6]

A version of the *second question* was addressed in some detail in the literature on bird song syntax (see for instance Lachlan 2006 for a review). For primate alarm calls, there are a few (occasionally anecdotal) reports of possible dialectal differences in call repertoires or realization.[7] We will not have anything to say about such differences; but we will claim that across Tai and Tiwai, Campbell's calls display dialectal variation in their *semantics*. Specifically, following Arnold et al. 2013, and on the basis of new data collected by these authors' teams, we will argue that the semantics of a particular alarm call, *krak*, is not the same in the Tai forest and on Tiwai island; as a first approximation, *krak* is often used as a leopard alarm call in the Tai forest, while it is used as a general alarm call on Tiwai island.

Concerning the *third question,* the literature on bird songs is quite a bit ahead of that on primate alarm calls: the formal properties of bird song syntax have been investigated in some detail (see Berwick et al. 2011 for a recent review). There is evidence of a sophisticated semantics in the alarm calls of blackcapped chickadees, studied in Templeton et al. 2005; but to our knowledge these have not given rise to formal semantic models. On the basis of a very simple (and preliminary) morphological and syntactic analysis, we will provide formal semantic models of Campbell's calls, ones that account for the limited dialectal variation that we find between the Tai forest and Tiwai island.

The rest of this article is structured as follows. In Section 2 we analyze the main morphological and syntax properties of the two dialects (with a simple root-suffix morphology, and a syntax that might be of a finite-state nature). In Section 3, we analyze general properties of their semantics. We explain in Section 4 why there are two 'dialects' in a non-technical sense: the same word is used in different ways on the two sites. In Section 5, we develop a simple formal model in which the difference between the two dialects is located in the lexical semantics: *krak* has a meaning of general alarm on Tiwai, but a meaning of leopard alarm in Tai. In Section 6, we explore an alternative analysis in which the meaning of the call is not subject to lexical variation, but a pragmatic operation of strengthening (akin to scalar implicatures) is responsible for the apparent dialectal variation. In a nutshell, the basic meaning of *krak* is always one of general alarm, but due to lexical competition this meaning is strengthened in Tai into something like *dangerous non-aerial predator,* and is thus naturally applied to leopards; but on Tiwai the result of this strengthening is nearly vacuous for lack of terrestrial predators, and as a result strengthening fails to apply. In Section 7, we briefly sketch some alternative directions that should be explored in future research, and we conclude with some open problems in Section 8.

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[5] In the data discussed by Ouattara et al. 2009b, the effect seems to be categorical: *boom boom* only occurs at the beginning of sequences. In the richer set of data we have access to, the effect is more gradient; we come back to this point in Section 2.3

[6] In fact, the semantic effect of adding *boom boom* to a sequence is dramatic enough that another species is cognizant of it. Specifically, Diana monkeys are sensitive to the presence or absence of *boom boom* at the beginning of a Campbell's call sequence. (Zuberbühler 2002, 'A syntactic rule in forest monkey communication').

[7]Here are a few examples:

–Cheney and Seyfarth 1990, cited in Skyrms 1996, mention the replacement of loud alarm calls given to dogs with shorter, quieter calls in vervet monkey populations that live in areas in which they are hunted by armed humans.

–Ouattara et al. 2009b discuss insertions of *krak-oo* after *boom boom* in one group of Tai Campbell's monkeys (group 1), but not in the other (group 2).

–Ouattara et al. 2009c found that RRA2 calls were present in captive female Campbell's monkeys but not in the wild, possibly suggesting the absence of this call from the wild female repertoire. The authors mention the 'controversial idea' that "the RRA2 call produced by captive individuals is a rare example of a socially transmitted vocal innovation, similar to the pant hoot variants observed in different chimpanzees (Marshall et al. 1999)" (they discuss further hypotheses as well).

–Marchall et al. 1999 discuss cases of dialectal variation in the acoustic realization of pant-hoot vocalizations of captive chimpanzees (they also review instances of possible instances of dialectal variation in other species, such as pygmy marmosets, red-chested moustached tamarins, and barabary macaques).

2 Morphology and Syntax of Campbell's Monkey Alarm Calls

2.1 Methods

Data on primate alarm calls are typically collected in three ways.

(i) *Naturalistic collection:* researchers may record naturally occurring triggering events, and see how they affect Campbell's monkey alarm calls; they may also record monkey alarm calls, and assess what effect they have on conspecifics (or in some cases on Diana monkeys).

(ii) *Artificially triggered calls:* researchers may perform controlled experiments in which they artificially place a trigger to assess what its effect will be on the calling behavior of the target species. Triggers are of two kinds: (a) auditory or visual stimuli corresponding to predators (e.g. playback of eagle shrieks and leopard growls, presentation of model eagles and leopards); (b) playback of alarm calls by Campbell's monkeys or Diana monkeys. (Inclusion of the latter could be useful because (1) Campbell's monkeys and Diana monkeys often form mixed-species groups, and thus are used to each other's calls; (2) it was shown in earlier research (e.g. Zuberühler 2000, 2002) that there is significant comprehension of calls across the two species; and (3) Campbell's male monkeys might be induced to 'translate' a Diana call more readily than they would another Campbell's monkey's call, since in the latter case their own calling behavior might be fully redundant.)

(iii) *Artificially triggered avoidance behavior:* researchers may also observe the target species to assess how it reacts to various alarm calls: for instance, a monkey may look up when hearing an eagle alarm call, or it may flee in the canopy when hearing a leopard alarm call (e.g. Seyfarth et al. 1980a, b).
In the present study, we base our analyses on data collected through methods (i) and (ii).

The data we analyze are subject to various sources of noise, both from the environment and from the calls themselves. At the 'environmental' level, there is uncertainty as to what is happening in the forest at any given moment, and although the responses we observe are probabilistically linked to the triggering event, various additional events may intervene over the course of the call sequences. At the 'linguistic' level, we work from transcriptions of acoustic signals that include calls and all sorts of noise. We will rely on the transcriptions obtained from previous research, but the categorization may have to be revisited in the future, both because of the quality of the signal and because the categorization may be challenged. For these reasons, we will base our conclusions on statistical analyses of tendencies we observe in the data. This need not entail that the underlying grammar is probabilistic.

2.2 Morphology

Earlier research (e.g. Ouattara et al. 2009a, b) identified five discrete elements in the alarm calls of male Campbell's monkeys of the Tai forest: *krak, hok, wak, boom, -oo*. *-oo* is only found after *krak*, *hok* and *wak*, and it is treated as a suffix by Outtara 2009a. *Boom,* which is produced with airsacs, is usually restricted to the initial position of a sequence, where it appears in duplicated form: *boom boom*. *krak* and *hok* can appear on their own, or suffixed with *-oo*. In the data described in Ouattara et al. 2009b, *wak* does not appear on its own, but it does in later data collected by the same team, and described below. As noted, we take the transcriptions as given, but it must be borne in mind that conclusions about the morphology, syntax and semantics ultimately depend on a proper phonetic and possibly phonological analysis, a question that should probably be revisited in the future. We thus define the morphology of the language under study as in (4) and (5).

(4) **Roots and affixes** [initial analysis]
a. Roots: boom, hok, krak, wak
b. Bound affixes: -oo

(5) **Lexicon** [initial analysis]
a. Every root is a word.
b. If R is a root different from *boom*, *R-oo* is a word.

2.3 Syntax

As mentioned, Ouattara et al. 2009b noted that *boom boom* only appears at the very beginning of sequences; but for the rest the authors were primarily concerned with the composition of sequences rather than with the order of elements that appeared in them. Here too, some methodological concerns are bound to affect future research: in field experiments, an external stimulus (e.g. a model eagle or leopard, or a played back sequence) triggers a sequence of alarm calls, whose beginning can thus be established more or less precisely; but what should count as the *end* of a sequence is less clear, and extraneous events may occur while a sequence is produced, which may affect its content.

What do Campbell's call sequences look like? With the abbreviations in (6), some example sequences are given in (7)-(9).

(6) **Abbreviations**
boom = b, krak = k, krak-oo = K, hok = h, hok-oo = H, wak = w, wak-oo = W

(7) **Examples from the Tai forest [new dataset, playback experiments]**
a1. Eagle shrieks
(i) hhhk
(ii)hhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhWhhhhWWhHWhhWWhWhhWhWh
WWwhWWWwWhhKhKKKWKWKKKhhKWWKKKKKKKKKKKKKKKKKKKKKKK

a2. Campbell eagle call:
(i) hhhhhhhhhhhHhhhhhHhHHHWWWWHHhHWWWWWWWWWWWWWWWWWW
(ii) KKKKKKKK

b1. Leopards growls
kkkkkkKK
kkkkkkkkkkkkkkkkkkk

b2. Campbell leopard calls
KKKKKKKKKKKKKKKKKKKKKKKKKKKKKKKKKKKK
KkKKKKKKKkkKKKKKKKKKKKKKKKKKKKKKKKKKkK

(8) **Examples from Tiwai island [new dataset, playback experiments]**
a1. Eagle shrieks
kkKKKKKKKKKK
KKKKKKKKKKKKKKKKKKKK

a2. Diana eagle calls
KKKKkkKK
hhhhhhhhhhhhhhhhhHhhhHhwhhKwwhhhWwWWWWWWWWWWh?hWWWWWWWWWWWWWW
WWKWWWWWWKKKWWWKWKKWWKkkkkk

b1. Leopard growls
KKKKKKKKKK
kkKKKKKKKKKKKKKKKKKKkkKKKKKKKKKK

b2. Diana leopard calls
KKKK
kkKKKKKKKK

c. Falling trees
BBKKKKKKK
KKKK

(9) **Examples from the Tai forest [data used by Ouattara et al. 2009]**

a1. Real eagle:	(i) hHWK (ii) HhKhWK
a2. Associated eagle call:	(i) K (ii) KWhK
a3. Model eagle:	(i) hKWKhHWK (ii) hWhWhWKWHWK
a4. Eagle call (shriek):	(i) KWK (ii) hHKWK
b1. Real leopard:	(i) k (ii) kKkK
b2. Associated leopard call:	(i) K (ii) kK
b3. Leopard call (growl):	(i) K (ii) kKk
b4. Model leopard:	(i) k (ii) kKkKkK
c. Tree / branch:	(i) BBK (nearly all of this type) (ii) BBKk (2 instances)
d. Inter-group:	(i) BBHK (ii) BBKHK
e. Cohesion and Travel:	BB (all of this type)

Given the initial data we have access to, the striking fact seems to be that a reasonable description can be provided with a finite state grammar (i.e. the very model that was *refuted* for human language by Chomsky 1957). Notably, there are quite a few cases in which there appears to be a varying number of repetitions of a call in a sequence. Sample finite state rules are given in (10), where * is a *modified* Kleene star, meaning: ≥1 occurrence (we put in parentheses optional components).

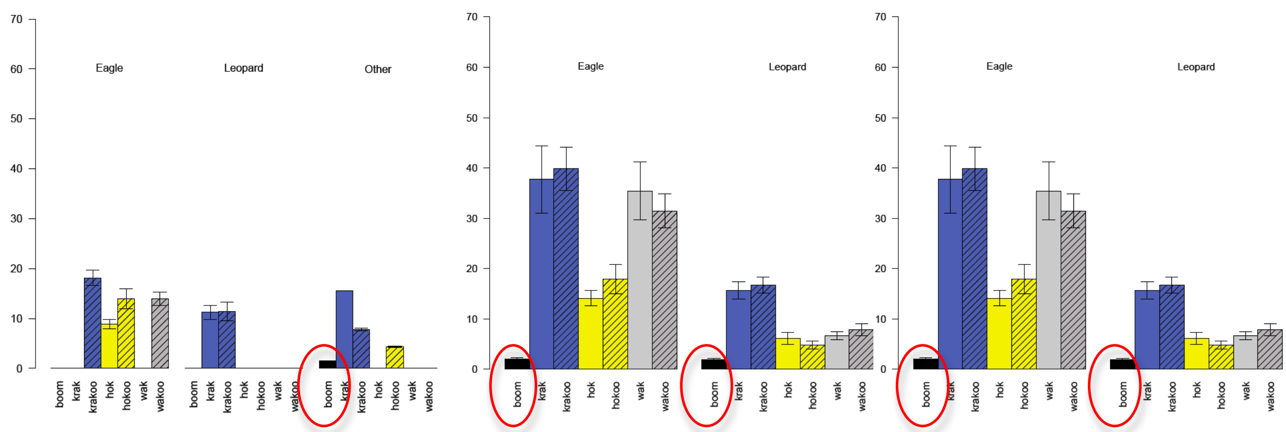
(10) **Sample syntactic rules (non-exhaustive)**

a. Cohesion and Travel:	bb
b. Tree/branch:	bb K* (k *)
c. Inter-group:	bb (K) H * K *
d. Leopard (various contexts):	k K*, k k*
e. Eagle (various contexts):	K K*, h*k, K*h*K*

It is far too early to make any subsantive claims about the syntax, which appears to be rather complex. But the fact that *boom* primarily occurs at the beginning of sequences is fairly clear, as can be seen in the dataset from Ouattara 2009a, b (Tai) and in the new datasets (from Tai and Tiwai) we investigate in this piece (it is worth pointing out that the positional data are clearer in the data from Ouattara 2009a, b).

(11) **Average position of *boom* in different datasets** (non-zero occurrences of *boom* are circled)

Dataset from Ouattara et al. 2009a, b (Tai) New dataset from Tai New dataset from Tiwai



Be that as it may, we leave a closer investigation of the syntax of Campbell's calls for future research (for better or worse, our semantic analysis will be largely independent from details of the syntax, due to the simplicity of the composition rules that we posit).

2.4 Quantitative analyses (new datasets from Tai and Tiwai)

The three datasets mentioned above are not homogeneous.

–The dataset from Tai used in Ouattara et al. 2009a, b involved more environments, many of them based on naturally occurring events; and they were transcribed by ear. 224 sequences were collected

in the Tai Forest, 43 were obtained from Eagle playback stimuli, 39 from Leopard playback stimuli and 142 were collected as various events happened in the forest (e.g., tree falls).
–The new datasets from Tai and Tiwai are primarily of type (ii) described above – they come from "playback experiments" (except for tree falls on Tiwai). We analyzed 217 call sequences containing a total of 8,868 individual calls (182 of these calls could not be transcribed with certainty, and they were thus disregarded in subsequent analyses). Both new datasets were coded with the help of a statistical analysis of the acoustic signal.
Since our main goal is to *compare* the two sites, we focussed on data that were otherwise as similar as possible, and hence analyzed the two new datasets, which were transcribed with comparable methods.[8] Unless otherwise noted, all quantitative data pertain to the new datasets; but we will make occasional reference to the older dataset from Tai when this can illuminate the analysis.

The stimuli used for the playback experiments were of different types: the predators' own calls, as well as Campbell or Diana alarm calls previously collected in response to these predators. As a first approximation, we aggregated the simuli depending on whether they corresponded to (a) the presence of an Eagle, or (b) the presence of a Leopard. On Tiwai, we also had access to 17 sequences corresponding to a general disturbance without a predator. Table (12) provides the number of call sequences of each type in the dataset we analyzed.

(12) Number of call sequences from our dataset in response to different playback situation

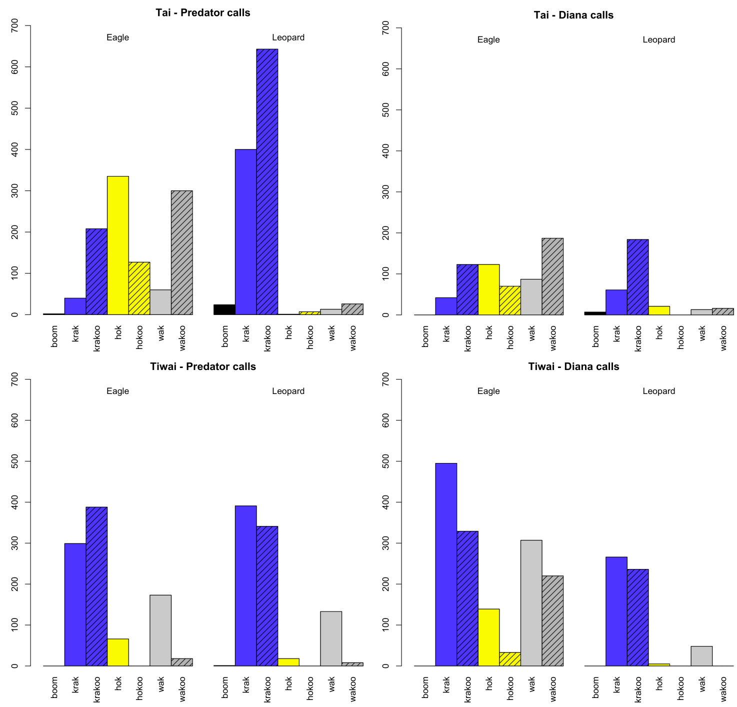
		Tai	Tiwai
Eagle	Shriek	24	23
	Diana	12	23
	Campbell	15	
Leopard	Growl	42	18
	Diana	12	16
	Campbell	15	
General Disturbance (tree fall)			17

2.4.1 Qualitative overview

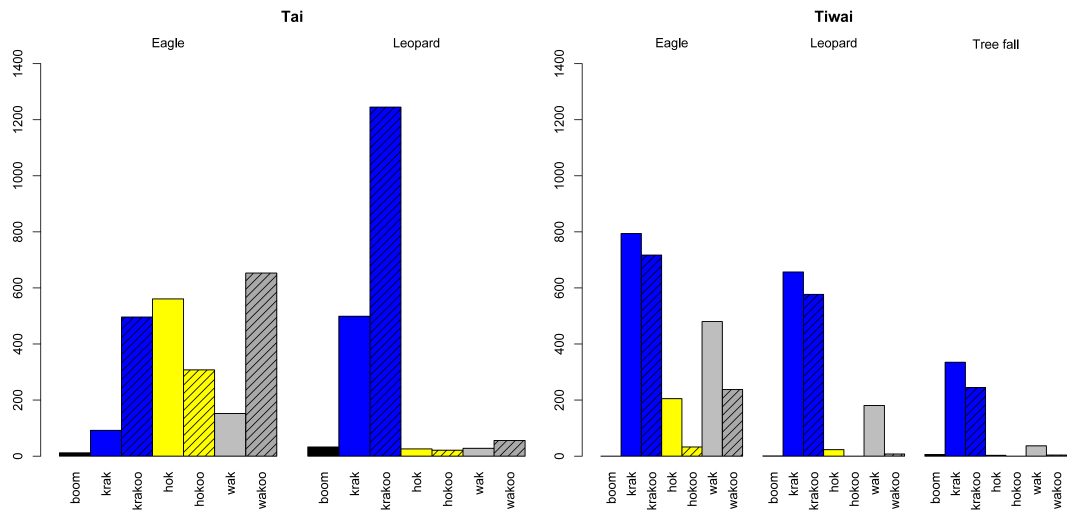
Figure (13) shows the distribution of each call type (*hok*, *krak*, etc.) in the different type of contexts on the two sites. We will focus attention on eagle- and leopard-related contexts broadly, irrespective of the types of stimuli used in these contexts (Predator Call, Campbell Call, Diana Call). Figure (14) thus displays an aggregated version of the data in Figure (13).

[8] Since we rely on transcriptions, it is necessary to check their reliability. We compared the results of two transcriptionists for n=1355 elements, and found agreement in 77% of all cases, corresponding to Cohen's Î°=0.713. The agreement is "substantial" according to the scale of Landis and Koch (1977), and "good" according to Fleiss' scale. An initial search showed no obvious pattern in the disagreements, suggesting that no systematic bias is introduced by the coding. A more thorough investigation is ongoing.

(13) Number of calls of different types in response to different playback stimuli in Tai and on Tiwai - detailed version



(14) Number of calls of different types in response to different types of playback stimuli in Tai and on Tiwai - aggregated version



2.4.2 *Specific meanings of calls:* hok *refers to eagles, and* krak *might refer to leopard (to be refined)*

These quantitative results give us an initial indication on the meaning of *hok* and *krak*:

(15) *Hok* is predominantly associated with eagles and *krak* is predominantly associated with leopards
a. *Hok* calls occur significantly more often in Eagle than in Leopard contexts ($\chi^2(1) = 631, p < .001$).
b. *Krak* calls display the opposite pattern: they predominantly occur in Leopard contexts ($\chi^2(1) = 36, p < .001$).

These results provide initial evidence that *hok* is an alarm call for aerial predators, while *krak* is an alarm call for terrestrial predators. Under these assumptions, the present result can be described as demonstrating that there is then an overwhelming proportion of appropriate uses of these calls.[9]

2.4.3 *Krak as a (more) general alarm call*

While *krak* and *hok* are predominantly associated with Leopard and in Eagle contexts respectively, this association is much stronger for *hok* than it is for *krak*: despite our initial result, *krak* is a more general alarm call than *hok*.

(16) *Krak* is a more general alarm call than *hok*
a. The association of *hok* with Eagle contexts is stronger than the association of *krak* with Leopard contexts. In other words, on the assumption that *hok* is appropriate in eagle-related contexts while *krak* is appropriate in leopard-related contexts, *krak* occurs more often in inappropriate (Eagle) contexts than *hok* occurs in inappropriate (Leopard) contexts: $\chi^2(1) = 368$, $p < .001$.[10] In other words, even though *krak* occurs more often in Leopard contexts, there are still many instances of it in Eagle contexts.
b. *Krak* can also be found in non-predator-related contexts: 335 such occurrences are found on Tiwai (where we have access to non-predator-related contexts), which accounts for 19% of the total number of kraks. By comparison, *hok* is only found 3 times in such contexts, or in 1.3% of all cases.

2.4.4 *Comparison between Tai and Tiwai*

In this section, we compare the use of calls in Tai and on Tiwai. The most important result concerns reactions to Eagle situations. These situations are ecologically plausible on both sites, since eagles are present both in Tai and on Tiwai (whereas leopards are present in Tai only); thus any difference found in such contexts cannot be attributed to superficial differences in how these situations are perceived. The result is as follows:

(17) In Eagle contexts, there are more *hoks* than *kraks* in Tai and more *kraks* than *hoks* on Tiwai.
In response to Eagle-related stimuli, we obtained more *hoks* (561) than *kraks* (92) in Tai, but crucially more *kraks* (794) than *hoks* (205) on Tiwai. This dissociation between the two sites is statistically significiant ($\chi^2(1) = 676$, $p < .001$).

In other words, on Tiwai, *krak* occurs frequently in Eagle situations, even more frequently than the expected specific Eagle call *hok*. This result can be understood if *krak* can serve as a general alarm call, as we suggest below.

As a control, we investigated Leopard situations. Recall that leopards are attested in Tai but not on Tiwai. Hence calls triggered in these situations may be subject to two sources of variation: broad differences between the two populations, and differences pertaining to the fact that Leopard stimuli have a different cognitive import on the two sites (since Tai monkeys know what leopards are, while Tiwai monkeys don't). In fact, we found no difference here, which suggests that these two sources are not responsible for the result in (17).

(18) There is no significant difference between Tai and Tiwai in Leopard contexts.
In response to Leopards, no difference is found between the ratio of *kraks* and *hoks* (657/23 in Tai and 499/26 on Tiwai): $\chi^2(1) = 1.49$, $p = .22$.

(19) There is a significant difference between the positive result about Eagle contexts and the negative results about Leopard contexts.
The difference found about Eagles (in (17)) is greater than the (absence of a) difference found about Leopards (in (18)): $\chi^2(1) = 922$, $p < .001$.

These results suggest that the Result in (17) reflects a linguistic reorganization due to a change in the environments, and in particular it is not due to a general tendency of Tai Campbell's monkeys to utter more *hoks* than their cousins from Tiwai island.

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[9] The same result holds if we restrict these analyses to each of the two sites.
[10] This result holds both in Tai ($\chi^2(1) = 39$, $p < .001$) and on Tiwai ($\chi^2(1) = 155$, $p < .001$).

3 Semantics of Campbell's Monkey Alarm Calls

Our main focus in this paper will be on the semantics. We leave out *wak* and *wak-oo* from the present discussion, as their distribution is not currently understood (their categorization might also raise difficulties, as the difference between *hok* and *wak* isn't always easy to perceive). Inferences about the meaning of different calls are drawn by considering sets of pairs of the form <triggering event, calling sequence> collected using the methods described in Section 2.1. Very roughly, the lexical meanings of the calls appear to be as follows (but this characterization will be refined and modified as we develop our analysis):

(20) **Informal description of the lexical meanings** (except *wak, wak-oo*)
a. boom boom: 'this is not a situation of predation'
b. krak-oo: 'there is an alert'
c. hok: 'there is an eagle'
d. hok-oo: 'there is an alert upwards'
e. krak: (i) 'there is a leopard' (Tai); (ii) 'there is an alert' (Tiwai)

One of the main puzzles concerns *krak*: it is often used as a leopard alarm call in Tai, and as a general alarm call on Tiwai.

We will develop a relatively standard model-theoretic semantics, which will be relativized to a model and a situation of utterance. As is standard, we write $I_{M,s}(w)$ for the lexical value of a word *w* in a model M and in a situation s, and $[[w_1 \ldots w_n]]^{M,s}$ for the semantic value in s of a sequence made of calls $w_1 \ldots w_2$. We will argue that an alarm parameter *a* (or later a time parameter) should be added as well at the compositional level, so that our 'official' notation will become: $[[w_1 \ldots w_n]]^{M,s,a}$ (we will write $I_{M,s}(w)$ rather than $I_{M,s,a}(w)$ because the alarm/time parameter will play no role at the lexical level). Since no operator ever manipulates the parameters M and s, we can usually leave them implicit, and thus write I(m) and $[[m_1 \ldots m_n]]^a$ instead of $I_s(m)$ and $[[m_1 \ldots m_n]]^{M,s,a}$.[11]

The rest of this discussion is organized as follows. Since most of the complexity lies in the lexical semantics, we start with the least sophisticated part of our analysis, which pertains to call composition: we define a single rule which interprets concatenation as conjunction, while ensuring that each occurrence of a call raises the value of the alarm parameter (it will later be reinterpreted in terms of a temporal parameter). We then define the lexical semantics of the calls whose semantics does not appear to be subject to variation, and illustrate the formal system with a few worked out examples. The analysis of *krak*, which is subject to dialectal variation, is the object of Section 4.

3.1 Rule of composition

How are the lexical meanings of calls combined? For human language, the semantics is usually taken to be compositional, in the (weak) sense that the meaning of an expression is determined by the meaning of its components[12] and the way they are put together by the syntax. From that perspective, it goes without saying that a proper semantics cannot be defined unless one understands the syntax. But as we noted above, the syntax of Campbell's monkey calls is anything but clear at this point (even if a finite-state analysis might be promising). Pending further investigation, we will assume that concatenation is basically interpreted as conjunction: a sequence w_1w_2 is simply interpreted as the conjunction of w_1 and w_2 (this is also the assumption that is often made about sequences of sentences in discourse in human language). Without further elaboration, however, this analysis would have an immediate drawback: it would fail to give any role to the numerous repetitions seen in Campbell's monkey alarm calls.

[11] The parameters M and s will play a role when we develop a theory of pragmatic strengthening in Section 6 (an operation of pragmatic strengthening will be assumed to take place unless it yields falsity for all (or most) situations s of a site/model M).

[12] The term 'strong compositionality' is usually applied when the meaning of an expression is determined from the meaning of its *immediate* components and the way they are put together.

Lemasson et al. 2010 note that in at least some cases the call rate – i.e. the number of calls per time unit – reflects as a first approximation the urgency of the threat (they write H, K, K_+, B for *hok, krak, krak-oo* and *boom* respectively; we have replaced their notation with ours):

> the call rates of four different alarm series (termed [hok], [krak], [krak-oo], and [boom] series) vary systematically as a function of context, associated behaviour, and identity of the caller. [krak-oo] series were given more rapidly to predation than non-predation events, [krak-oo] and [krak] series more rapidly to visual than auditory predator detection, and [hok] series more rapidly while counterattacking an eagle than staying put.

In order to keep the analysis as simple as possible, we will initially assume that each occurrence of a call raises a general and unspecific alarm level[13] (in our second, time-sensitive model, re-iteration of a call will have a more direct effect: it will indicate that the caller *remained* in a state of alarm for a certain period of time; in effect, the role of the alarm parameter will be taken over by a time parameter). Importantly, however, this parameter will not exhaust the contribution of a call: the first occurrence of any given type always has a *bona fide* truth-conditional contribution.[14] Technically, this can be achieved by relativizing our interpretation function $[\![\ .\ ]\!]^{M,s}$ to an alarm parameter a, and to posit the rule in (21), where I is the interpretation of lexical items, and 1 and 0 are used for true and false, as is standard; as announced, we will write $[\![\ .\ ]\!]^a$ instead of $[\![\ .\ ]\!]^{M,s,a}$.

(21) Compositional Semantics [time-insensitive version, to be revised]

For any alarm level a, for any word w, for any string S,

a. $[\![w]\!]^a = 1$ iff $I(w) = 1$ and the alarm level is at least a.

b. $[\![w\ S]\!]^a = 1$ iff $[\![w]\!]^a = 1$ and $[\![w]\!]^{a+1} = 1$

A schematic example will help see the rule in action. Suppose that we are evaluating the calls w, ww and ww' relative to an initial alarm parameter of 0. The effects are given in (22): each call contributes its lexical meaning, and the total number of calls determines the alarm parameter.

(22) a. $[\![w]\!]^0 = 1$ iff $I(w) = 1$ and the alarm level is at least a, iff $I(w) = 1$.
b. $[\![ww]\!]^0 = 1$ iff $I(w) = 1$ and $[\![w]\!]^1 = 1$, iff $I(w) = 1$ and the alarm level is at least 1.
c. $[\![ww']\!]^0 = 1$ iff $I(w) = 1$ and $[\![w']\!]^1 = 1$, iff $I(w) = 1$ and $I(w')$ and the alarm level is at least 1.

It is immediate that if the initial alarm level is zero, the final alarm level divided by the time elapsed since the beginning of the sequence will provide the average call rate, and hence an approximation of the observations in Lemasson et al. 2010.[15] It is clear that the role of the call rate could be captured in several other ways; the device of the alarm parameter is only intended to make the semantics particularly simple.

3.2 Lexical semantics

Let us now turn to the lexical semantics, where most of the action will be. We start with the subpart of the calls whose semantics will remain essentially constant across our two models. We follow Ouattara et al. 2009b in taking *boom boom* to indicate that the context is one that doesn't involve predation; we argue that *hok* involves aerial predators (though this analysis will be refined later); and that *-oo* is a suffix that broadens the meaning of a root and probably makes its informative content less urgent.

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[13] There are other species in which number of calls is correlated with intensity. For instance, Arnold and Zuberbühler 2012 note that the distance traveled by putty-nosed monkeys after hearing a *pyow hack* sequence is an increasing function of the total length of the sequence, or of the number of *pyows* uttered (in the authors' data, the two variables are confounded).

[14] In the second model we develop below, the semantic content of any call is relativized to the precise time of its utterance, and for this reason two calls uttered at t and t+1 don't have the same informational content, since one provides information about the source's state of mind at t, and the other at t+1.

[15] We might want to have a slightly more refined version of rule (21)b, one in which the alarm level is *not* raised by *boom boom,* which indicates that the context is not one of predation. This wouldn't make much practical difference, however, since *boom boom* is usally not repeated and hence won't have a significant effect on the alarm level.

❑ *boom boom*

Ouattara et al. 2009b described *boom* as being indicative of non-predation contexts (here too, we replace the authors' abbreviation of calls with ours):

Nonpredation events were characterized by the production of two boom calls, which could be given alone (to indicate group movement) or which could introduce subsequent calls (100%, *n* =142 cases, all eight males). In response to tree falls, the booms preceded a series of [krak-oo] calls. In response to neighbors, the booms preceded a series of [hok-oo] calls, followed by a series of [krak-oo] calls.

It is interesting to note that in the dataset analyzed in Ouattara et al. 2009b the effect is categorical: *boom* only occurs in non-predation contexts. The facts facts are less clear in the datasets we analyze in the present piece, as shown in (23).

(23) **Use of *boom* in three datasets**
Number of sequences containing *boom* / Total number of sequences

Disturbance	Tai from Ouattara et al. 2009b	Tai new dataset (this paper)	Tiwai new dataset (this paper)
Leopard	**0/39**	16/69	1/34
Eagle	**0/43**	6/51	0/46
Tree	**53/53**	-	4/17
Inter-group	**76/76**	-	-
Cohesion and Travel	**13/13**	-	-

Despite these subtleties, we will assume that Ouattara et al. 2009b are essentially correct. We will thus posit the lexical rule in (24), where we have made the choice of treating *boom boom* as a single lexical item (since *boom* usually occurs in duplicated):

(24) Meaning of *boom* (preliminary)
$I_{M,s}$(boom-boom) = 1 iff there is a disturbance but no predator in s

❑ *hok*

Ouattara et al. 2009b noted that *hok* and *hok-oo* are often associated with the presence of eagles. Restricting attention for the moment to *hok*, we categorized its occurrences as 'appropriate' (given the hypothesis) if they appear in contexts that involve eagles, namely ones in which the call was triggered by real or model eagles, or eagle shrieks, or Campbell or Diana calls normally associated with eagles; occurrences of *hok* that appear in other contexts may be called 'inappropriate'. As we saw in Section 2.4.2, under this assumption most uses of *hok* are in fact appropriate.

Using the same format as in (24), we can provide a preliminary interpretive rule for *hok*:

(25) Meaning of *hok* (preliminary)
$I_{M,s}$(hok) = 1 iff there is an aerial predator in s

Importantly, the existence of a call solely or primarily used for raptors is common across primates, and it is found in species that have only the most distant of relationships with Campbell's monkeys. As we mentioned in Section 1.3, the same finding was made across several primate species, as mentioned by Wheeler and Fisher 2012. While we will consider a refinement of the lexical meaning of *hok* in Section 5.3, we will preserve the consequence that in most cases *hok* warns of the presence of an aerial predator. (We will also posit that despite initial appearances *krak* is a general alarm call, but the argumentation will be indirect.)

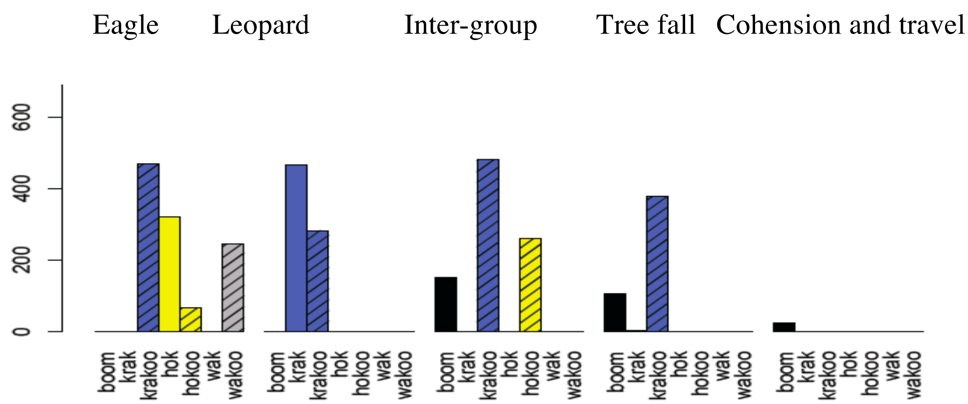
❑ *-oo*

We will work on the assumption that *-oo* has a stable compositional meaning, i.e. that it modifies in a regular way the meaning of the root it attaches to. Furthermore, we assume that *-oo* attached to a root *R* attenuates or broadens the meaning of *R*. An initial motivation for this assumption lies in the comparative distribution of *krak* vs. *krak-oo* in the Tai forest: there more non-leopard-related uses of *krak-oo* than of *krak*, as shown in (26).[16]

(26) *Krak-oo* occurs more frequently in non-leopard-related situations than *krak* does
a. 84% of all *kraks* are found in Leopard situations (499/591).
b. By contrast, 'only' 72% of all *krak-oos* are found in Leopard situations (1245/1741) ($\chi^2(1) = 38$, $p < .001$).

The Tai dataset used in Ouattara et al. 2009a, b is particularly informative in this connection because it contains more triggering situations than the new datasets we otherwise focus on. And it is striking in this case that *-oo*-modified forms (hatched bars) occur in many environments in which unmodified forms (open bars) do not occur: as shown in (27), *krak* doesn't occur in Eagle, Inter-group, and Tree fall situations, but *krak-oo* does; and *hok* doesn't occur in Inter-group situations, but *hok-oo* does. The converse situation (with an unmodified form occurring in an environment in which the modified form doesn't occur) doesn't arise here.

(27) **Distribution of modified and unmodified forms in the dataset used in Ouattara et al. 2009a, b**



(It must be mentioned, however, that in the two recent datasets we study in this paper, some facts go in the opposite direction, as seen in the detailed distribution of calls in (13): in Tai Diana Leopard contexts and in Tiwai predator Eagle contexts, there are respectively 21 and 66 *hok*'s, but no *hok-oo*'s.[17])

Using the same format as in (24) and (25) above, we can define the semantic contribution of *-oo* as in (28):

(28) Meaning of *-oo* (to be revised)
for any root R different from *boom-boom*[18],
$I_{M,s}(R\text{–oo}) = 1$ iff in s there is a disturbance that licenses the same attentional state as if $I_{M,s}(R) = 1$, or in other words: in s there is a disturbance that licenses the same attention state as situations s' such that $I_{M,s'}(R) = 1$.

Putting together our lexical rule for *hok* and our rule for *-oo*, we can obtain a lexical meaning for *hok-oo*, as shown in (29):

(29) $I_{M,s}(\text{hok–oo}) = 1$ iff in s there is a disturbance that licenses the same attentional state as if $I_{M,s}(\text{hok}) = 1$,

[16] The effect goes in the same direction for the *hok/hok-oo* pair but to a much weaker degree (96% of *hoks* are found in Eagle situations (561/587) while 94% of *hokoos* are found in Eagle situations. $\chi^2(1) = 1.3$, $p = .26$). Note however that along that measure the specificity of *wak* (84% in Eagle situations) seems lower than the specificity of *wakoo* (92% in Eagle situations).
[17] In Tiwai Diana leopard contexts, there were also *hok*'s and no *hok-oo*'s, but it is harder to assess the significance of this result because there were only 5 *hok*'s.
[18] If the lexicon excludes *boom-boom-oo*, this precaution will be unnecessary. This might also be excluded for articulatory reasons or for some semantic reason (e.g. because *boom-boom* does not license any attentional state per se).

iff in there is a disturbance that licenses the same attentional state as if there is an aerial predator in s.

In other words, *hok-oo* warns the hearer to be in an attention state of the sort that one should be in for an aerial predator, but without providing the information that there is in fact an aerial predator. So this could be a message to pay attention to what is going on upwards without a commitment to the presence of an aerial predator (but without excluding it either). It is immediate given this definition that the meaning of *hok-oo* is broader than that of *hok*: the latter is only made true if an aerial predator is present; while *hok-oo* is made true in the same situations, but also in ones in which there is no predator.

One fact is striking in this respect: in naturalistic data originally discussed in Ouattara et al. 2009a, b, *hok-oo* is used in each of the three instances of inter-group encounters (in combination with *krak-oo)*; the same situations do not give rise to any unmodified *hok*, as shown in (30).

(30) **Occurrence of *hok-oo* vs. *hok* in inter-group encounters in the Tai dataset used in Ouattara et al. 2009a, b**
(B = boom; H = hok-oo; K = krak-oo; S* represents an uninterrupted string of one or more S's)

Pattern	Number of sequences with the relevant pattern
a. BBH*K*	66
b. BBH*K*H*K*	1
c. BBK*H*K*	9

The occurrence of *hok-oo* in inter-group encounters need not be surprising if we assume that most of encounters occur high in the trees, which might license an 'upwards' attentional state, but of course without any implication that an eagle is present. The occurence of *hok-oo* in these contexts might provide additional motivation for taking *-oo* to attenuate or broaden the meaning of the root it attaches to.

One final set of observations might be telling. While in many environments suffixed *R-oo* calls are more frequent than unsuffixed *R* calls, the predominance of the suffixed form is stronger as a reaction to Campbell calls than as a reaction to Diana calls or to predator calls, as summarized in (31).

(31) The predominance of suffixed *R-oo* calls is greater as a reaction to Campbell calls than as a reaction to Diana or to predator calls
a. Suffixed *R–oo* calls are more frequent than root *R* calls in conditions triggered by Campbell calls (888 vs 162).
b. The corresponding numbers are 1398 vs 1607 with Diana calls and (2066 vs 1929) with predator calls.
c. Crucially, the difference between a. and b. is statistically significant: ($\chi^2(1)=456$, $p < .001$).

This might conceivably be interpreted as follows: in conditions triggered by Campbell calls, Campbell's monkeys only need to *complete* the calls they have heard, and for this reason the less specific *-oo*-modified calls can be used. By contrast, in Diana or predator contexts, they must convey the *full* information about the nature of the threat, and hence unsuffixed (and thus more specific) calls must be used.

3.3 Examples

Putting together the results of Section 3.1 and 3.2, we can derive truth conditions for some very simple sequences. Consider first a single *hok-oo* call, whose lexical semantics was discussed in (29). Assuming that the initial alarm level is 0 (and can never fall below 0), we can apply rule (21)a to obtain the simple result in (32):

(32) $[\![\text{hok-oo}]\!]^0 = 1$ iff I(hok-oo) = 1 and the alarm level is at least 0,
iff there is a disturbance that licenses the same attentional state as if there is an aerial predator (and the alarm level is at least 0 – a condition which is always met).

When the call is repeated, say twice, we need to apply rule (21)b; the result is the same as in (32), except that for the resulting sentence to be true the alarm level must be of at least 2.

(33) $[\![\text{hok-oo hok-oo hok-oo}]\!]^0 = 1$ iff $[\![\text{hok-oo}]\!]^0 = 1$ and $[\![\text{hok-oo hok-oo}]\!]^1 = 1$
iff $[\![\text{hok-oo}]\!]^0 = 1$ and $[\![\text{hok-oo}]\!]^1 = 1$ and $[\![\text{hok-oo}]\!]^2 = 1$
iff there is a disturbance that licenses the same attentional state as if there is an aerial predator and the alarm level is at least 2.

We can also consider a simple sequence *boom-boom hok-oo hok-oo hok-oo,* whose truth conditions are obtained from those of *hok-oo hok-oo hok-oo* in (33), together with our assumptions about the meaning of *boom-boom* in (24); this kind of sequence is of empirical interest, since it appears at the beginning of the numerous sequences following patterns (30)a and (30)b discussed above.

(34) $[\![\text{boom-boom hok-oo hok-oo hok-oo hok-oo}]\!]^0 = 1$
iff $[\![\text{boom-boom}]\!]^0 = 1$ and $[\![\text{hok-oo hok-oo hok-oo}]\!]^1 = 1$
iff there is a disturbance but no predator and there is a disturbance that licenses the same attentional state as if there is an aerial predator and the alarm level is at least 3.

As a result, this type of sequences might be expected to arise in environments in which there is no predator (and thus no eagle), but something is still happening in the canopy; this might account for the naturalistic observations in which *hok-oo* is used in inter-group encounters, as was noted above.

While *boom-boom* won't play a role in what follows, we will continue to assume that (i) concatenation is interpreted as some version of conjunction, as we stated above; (ii) *hok* has a meaning related to aerial predators (though we will fine-tune the details); (iii) *-oo* has a compositional contribution that attenuates in some way the meaning of the root it attaches to.[19]

It remains to analyze the semantics of *krak*. We will argue in Section 4 that its use is subject to variation: even though eagle situations are presumably of the same type in Tai and on Tiwai, they give rise to very different call sequences, with numerous *kraks* on Tiwai but not in Tai. In Section 5, we will develop a lexical account of the distinction, one in which *krak* is a general alarm call on Tiwai and but a ground predator call on Tiwai. In Section 6, we will develop an alternative analysis in which *krak* has the same meaning on both sites, but the *pragmatics* of call use interacts with the context in such a way as to give rise to a difference – despite the fact that all the rules are the same on both sites.

(A terminological note is in order: we have been using the term 'dialect' informally, to refer to an apparent difference in the use of a call across the two sites. In the first analysis to be developed, there will be a dialectal difference in the technical sense: *krak* will have different lexical entries across the two sites. In the second theory, the *very same system* will be posited for the two sites, but its interaction with the context – technically: with the model parameter – will account for the difference in use.)

4 Two Dialects: Tai vs. Tiwai

Following Arnold et al. 2013, we now argue that Campbell's monkeys speak different dialects in the Tai forest and on Tiwai island; specifically, the call *krak* is used with different functions in the two locations (the next sections will develop two competing models of why this is so).
–As we noted in connection with Diana monkeys, the Tai and Tiwai environments differ in terms of relevant predators: Tai has eagles and leopards, whereas Tiwai has eagles and no leopards.
–To our knowledge, there is no evidence of a sizable genetic difference between Campbell's monkeys in Tai vs. on Tiwai; if so, we should assume that whatever innate specifications the calling system has does not significantly differ across the two sites, so that a unified theory is called for.[20]

[19] In the first model we develop, we will preserve rule (28), which predicts that *R-oo* should have a broader range of uses than *R*. In our second model, *-oo* will *restrict* the meaning of *R*, but will specify that the denoted threat is *weak* among those that license *R*. The attenuating function of *-oo* is thus implemented very differently in the two models.
[20] We do not know of any genetic data comparing Tiwai and Tai Campbell's monkeys. However, the entire guenon clade evolved relatively recently (maybe in the neighborhood of 200,000 years ago), and until a few hundred years ago the Campbell's monkeys were part of one continuous population from Ghana to Sierra Leone; this wouldn't seem to offer not enough time for major genetic changes to emerge.

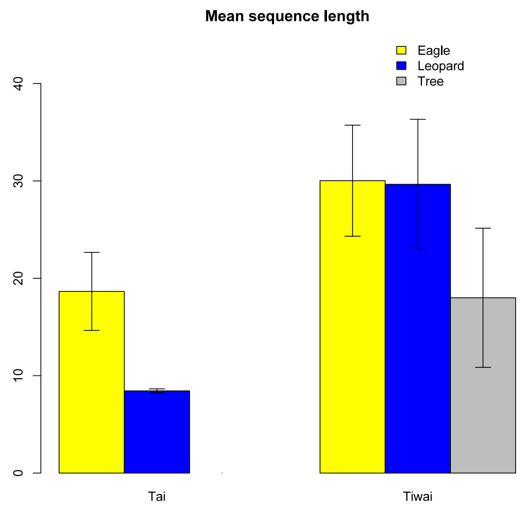
We noted in our discussion of Stephan and Zuberbühler's (2008) analysis of Diana monkeys that the difference in calling behavior found between Tiwai and Tai could potentially be due to a difference in *life experience* rather than in the *meaning of the sequences* themselves. The heart of the matter was that the difference concerned calling behavior to leopard-related stimuli, which are unknown on Tiwai – hence the monkeys' *cognitive* reaction might be understandably different from that of their leopard-savvy cousins from Tai. In order to construct an argument in favor of a *linguistic* difference, we need to show that in one and the same cognitive situation, Tiwai monkeys call differently from Tai monkeys. Precisely this case can be found for Campbell's monkeys. Although the relevant ecological difference between Tai and Tiwai pertains to leopards, Campbell's monkeys call to *eagles* in a different way on the two sites. This is the sign of a sophisticated system, one in which either (a) the meanings expressed by the calls are not exactly the same across the two sites, or (b) these meanings or the decision to use them is sensitive in some way to the *environment* of the speaker rather than just to the narrow situation in which calls are uttered. Given some plausible assumptions, the opposite theory, stated in (35), can be refuted:

(35) **Theory 0 (to be refuted)**
(a) The lexical meaning of calls is entirely innate.
(b) i. These meanings are only sensitive to the narrow situation in which they are used.
ii. The choice of the messages (i.e. truth conditions) uttered is only determined by the narrow situation in which they are used.

Let us assume that eagle-related situations are the same in all relevant respects in Tai and on Tiwai. By (35)b(ii), the same messages are expressed in the same situations at the two sites. By (35)a, the words have the same meanings at the two sites, and by (35)b(i) these meanings have the same truth conditions in the same situations. This predicts that the very same calls should be found in eagle-related situations at the two sites – which is exactly the opposite from what we found: as we saw in Section 2.4.4, *krak* is almost never used to call to eagles in Tai, but is very common in such situations on Tiwai. Of course this makes much functional sense: a leopard alarm call might have great survival value in the Tai forest, but none whatsoever on Tiwai island – and thus it is 'reasonable' for Tiwai monkeys to use this call for different purposes. We will see in the next two sections how a formal model can account for these differences.

Note that there might well be further differences between the dialect used on Tiwai and that practiced in Tai. For instance, as shown in (36), data on sequence length differ across Tai and on Tiwai. First, sequences are generally longer on Tiwai. Second, while on Tiwai Leopard and Eagle contexts give rise to sequences of equal length, in Tai Eagle sequences are longer than Leopard sequences.

(36) Mean sequence length in Tai and on Tiwai



We do not have anything to say about this difference at this point. Similarly, it certainly cannot be excluded that there are further differences within each population, with different groups of Campbell's monkeys (or even different individuals) speaking in a different way (see fn. 7); we leave these issues for future research.

5 A Lexicalist Analysis

We will now develop a lexical account of the distinction between the meaning of *krak* in the Tai forest and on Tiwai island. As a first approximation, we might want to say that in Tai the meaning of *krak* involves leopards/ground predators, whereas on Tiwai the same word is used as general alarm call. While in human languages dialectal variation usually involves both differences in morphology and in meaning, there are cases in which the same word (possibly with slightly different pronunciations) has different meanings: *pants* is normally used to refer to underwear in Great Britain, but to trousers in the US[21]; the situation might be similar in the case of *krak* (with the difference that misunderstandings among speakers of different dialects might have more momentous consequences). Still, as we will now see a lexical analysis of this dialectal difference must be made more complex if it is to stick to our assumption that *krak-oo* is compositionally derived from *krak*.

5.1 Krak-oo as a general alarm call in Tai

We assumed in (28) that *-oo* modifies in a regular way the meaning of the root it attaches to. But it can be shown that in Tai *krak-oo* has a meaning of general alarm; this implies that we will need a kind of ambiguity in which *krak* has a (possibly innate) meaning of general alarm, which (i) might hold on Tiwai as well, and (ii) feeds the semantic derivation of the meaning of *krak-oo;* but it *also* has a strengthened, acquired meaning which conveys information about leopards/ground predators – and this meaning only arises in Tai. The argument that *krak-oo* serves a general alarm call in Tai is straightforward: as we showed in Section 2.4.3, it occurs in high numbers in all triggering contexts.

5.2 Analysis

To account for these facts, we will posit that (i) *krak* has a (possibly innate) meaning of general alarm in Tai and on Tiwai alike, but that (ii) it has an acquired meaning of ground predator-related alarm in Tai. Technically, we need to assume an ambiguity whereby the suffix *-oo* is added to the root $krak^1$, whereas the word *krak* without *-oo* is interpreted as $krak^2$, which has a stronger meaning. Our morphological and semantic assumptions are summarized below:

[21] This and other cases are discussed in: http://www.srcf.ucam.org/camling/proceedings/rocavarela.pdf

(37) **Roots and affixes** [ambiguity-based analysis]
a. Roots: boom, hok, $krak^1$, wak; in Tai only: $krak^2$
b. Bound affixes: -oo

(38) **Lexicon** [revised analysis]
a. Every root is a word.
b. If R is a root different from *boom* and *krak*^{2}, *R-oo* is a word.

(39) Innate meanings (setting aside *wak*)
-Roots
a. $I_{M,s}(krak^1) = 1$ iff there is a disturbance in s
b. $I_{M,s}(hok) = 1$ iff there is an aerial predator in s
c. $I_{M,s}(boom\text{-}boom) = 1$ iff there is a disturbance but no predator in s
-Affix
d. for any root R different from *boom*,
$I_{M,s}(R–oo) = 1$ iff there is a disturbance that licenses the same attentional state as if $I_{M,s}(R) = 1$, or in other words: there is a disturbance that licenses the same attention state as situations s' such that $I_{M,s'}(R) = 1$.

(40) Acquired meaning of *krak* in Tai only
$I_{M,s}(krak^2) = 1$ iff there is a leopard in s.

5.3 Refinements and Problems

5.3.1 Refinement I: hok

The meaning we posited for *hok* predicts that it should only be used in eagle-related situations. But in Tai, *hok* occasionally appears as a reaction to leopard calls from other Campbell's monkeys; this does not follow from our current semantics. This problem could potentially be solved by giving a weaker semantics to *hok*, with (41)b replacing (41)a:

(41) a. Old rule: $I_{M,s}(hok) = 1$ iff there is an aerial predator in s
b. Revised rule: $I_{M,s}(hok) = 1$ iff there a threat according to a non-terrestrial source in s, i.e. there is a non-terrestrial predator in s or in s there is a non-terrestrial creature informing of a threat.

Presumably Campbell's monkey calls originate from trees, which might explain why *hok* with the revised meaning in (41)b is used in these cases.[22]

5.3.2 Refinement II: possible mechanisms of evolution of the leopard meaning of krak *in Tai*

To go further, we should establish (i) whether Campbell's monkeys have *in principle* the ability to learn new meanings, and (ii) by which mechanism the 'leopard' meaning could come to be added on top of the 'general alarm' meaning.

We do not know of direct evidence pertaining to Campbell's monkeys' ability to learn new meanings. Still, prior research displayed evidence of flexibility in two domains. First, the detailed acoustic realization of (largely innate) calls of female Campbell's monkeys appears to be influenced by that of the femals they are 'friends' with (specifically, acoustic similarity among the calls of dyads of female Campbell's monkeys was shown by Lemasson et al. 2011b to be better predicted by *social affinity* than by *genetic similarity*; see also Lemasson et al. 2004, 2005). Second, it was also shown that turn-taking in conversation is subject to acquisition: the rate of 'inappropriate' repetitions (in which a Campbell's monkey fails to respect rules of turn-taking) was shown by Lemasson et al. 2011a to be greater in youngsters than in adults. Needless to say, the existence of acoustic or pragmatic flexibility does not directly answer the crucial question of *semantic* flexibility, which we leave for future research.

Now what about possible mechanisms of historical evolution of a 'leopard' meaning of *krak* in a population that originally started with a 'general alarm' meaning? We would like to show that a population that *can* in principle acquire a leopard meaning has an *advantage* to do so. To see what the

[22] We noted in (30) that in the Tai dataset used by Ouattara et al. 2009a, b, inter-group encounters give rise to *hok-oo* but not *hok*. This still follows from our revised analysis of *hok*, as in these cases the groups encountered do not constitute the source of an alarm call.

formal issues are, let us consider the problem in a very simplified form, with just 1-call sequences; and let us restrict attention to the use of *hok* and *krak* in Leopard and in Eagle situations. We assume that a Tai monkey can adopt a *strategy* that defines its behavior as a sender and receiver of alarm signals. We will assume that strategies are deterministic ('pure', in game-theoretic parlance): a signal deterministically gives rise to a first reaction, which we assume to be of just two types: 'leopard-appropriate' or 'eagle-appropriate'; and we also take situations to be of two types: 'leopard situations' or 'eagle situations', and to deterministically give rise to a call. We further assume (very simplistically) that the Sender of the signal and the Receiver derive the same pay-off from the interaction, which counts as successful to the extent that the information available is successfully transmitted; and that in an interaction each individual knows the strategy of the other. In principle, then, the relevant behavior of any individual i is defined by a pair $\langle R_i, S_i \rangle$, where R_i is its strategy as a receiver ('which reaction should I adopt when I hear *krak* or *hok*?') and S_i is its strategy as a sender ('which call should I use in Leopard or in Eagle situations?').

Since *hok* is innately specified as an eagle call, the sender has only two possible strategies:

(42) Possible strategies for the sender
$S_{distinct}$ = <leopard_situation → krak, **eagle_situation → hok**>
$S_{trivial}$ = <leopard_situation → krak, **eagle_situation → krak**>

Similarly, a receiver that hears *hok* knows that the situation is an eagle-related one, so the only choice concerns the interpretation of *krak*:

(43) Possible strategies for the receiver
$R_{distinct}$ = **<krak → leopard-appropriate_reaction**, hok → eagle-appropriate_reaction>
$R_{trivial}$ = **<krak → eagle-appropriate_reaction**, hok → eagle-appropriate_reaction>

Let us start by considering the Nash equilibria of this game, i.e. the pairs $\langle R, S \rangle$ for which neither the receiver nor the sender has an interest in deviating from its strategy given what the other player's strategy is. There are four pairs to consider: $\langle R_{distinct}, S_{distinct} \rangle$, $\langle R_{distinct}, S_{trivial} \rangle$, $\langle R_{trivial}, S_{distinct} \rangle$, $\langle R_{i\ trivial}, S_{j\ trivial} \rangle$.

Under natural assumptions, $\langle R_{distinct}, S_{distinct} \rangle$ is a strict Nash equilibrium, in the sense that any deviation from either strategy yields smaller pay-offs. In $\langle R_{distinct}, S_{distinct} \rangle$, information is perfectly transmitted and thus pay-offs are at their maximum. By contrast, if the receiver adopts strategy $R_{trivial}$, the receiver will have an inappropriate response in leopard situations; and if the sender adopts strategy $S_{trivial}$, the sender will cause the receiver to have an inappropriate response in eagle situations.

By contrast, $\langle R_{distinct}, S_{trivial} \rangle$ and $\langle R_{trivial}, S_{distinct} \rangle$ are not Nash equilibria, not even weak ones (in a weak Nash equilibrium, we don't require that deviations be penalized, but only that they should not be rewarded). In the first case, the sender can yield superior pay-offs by adopting $S_{distinct}$ rather than $S_{trivial}$, as this will provide information that the receiver will use (since the receiver is using strategy $R_{distinct}$). In the second case, the receiver can yield superior pay-offs by adopting $R_{distinct}$ rather than $R_{trivial}$, as this will allow the receiver to use the information conveyed in the sender's (non-trivial) signalling strategy.

Still, in some situations there is another Nash equilibrium, albeit a weak one – namely $\langle R_{trivial}, S_{trivial} \rangle$. Consider the following scenario: on average (i.e. without specific information about the particular predator), eagle-appropriate reactions yield a greater pay-off than leopard-appropriate reactions. If so, the receiver will produce a *smaller* pay-off by using $R_{distinct}$ than by using $R_{trivial}$, since in that case the receiver will systematically adopt the less optimal leopard-appropriate reaction. As for the sender, it will produce the very same pay-offs by adopting $S_{distinct}$ rather than $S_{trivial}$, since the information conveyed by the signal ('leopard situation' vs. 'eagle situation') will systematically be disregarded by the receiver.

Can we appeal to *evolutionarily stable strategies* to rule out $\langle R_{trivial}, S_{trivial} \rangle$? According to the standard definition, strategy i is evolutionarily stable just in case for all alternative strategies j, either (1) the payoff of i against i is greater than the payoff of j against i, or (2) i and j have equal payoffs played against i, but i has a greater payoff than j when played against j (see for instance Skyrms 1996). The basic intuition is that i is evolutionarily stable just in case it can successfully resist invasion by mutants j, which is the case if mutants fare less well against non-mutants than the majority non-mutants do against each other (Condition (1)); or mutants and non-mutants fare equally

well against non-mutants, but non-mutants fare better against mutants (Condition (2)). Now consider the problematic case in which on average eagle-appropriate reactions yield a higher pay-off than leopard-appropriate reactions.
(i) First, it is clear that $<R_{distinct}, S_{distinct}>$ is evolutionarily stable, since it is a strict Nash equilibrium and thus satisfies Condition (1).
(ii) Second, $<R_{trivial}, S_{trivial}>$ is not quite evolutionarily stable. There are two relevant observations.
–First, deviation from $R_{trivial}$ will be penalized. The reason is this: $S_{trivial}$ conveys no information whatsoever to the receiver, hence the best reaction is to always have an eagle-appropriate reaction. Since $S_{trivial}$ only yields utterances of *krak*, this means that against a non-mutant population that plays $S_{trivial}$, a mutant has no choice but to display an eagle-appropriate reaction when *krak* is heard, and thus to play $R_{trivial}$ (there is no other choice because we have taken the meaning of *hok* to be systematically eagle-related).
–Second, however, deviation from $S_{trivial}$ will not be penalized. This is because against a population of mutants and non-mutants that play $R_{trivial}$, the choice of the signalling strategy doesn't matter, and $S_{distinct}$ yields the same pay-offs as $S_{trivial}$.

So in principle $<R_{trivial}, S_{trivial}>$ could be invaded by $<R_{trivial}, S_{distinct}>$, although the *mechanism* of the invasion is not clear (since the pay-offs aren't greater with the mutant than with the mutant strategy). Importantly, however, if by some mechanism $<R_{trivial}, S_{distinct}>$ prevails, it will eventually be invaded by $<R_{distinct}, S_{distinct}>$. Needless to say, this is only the beginning of a sketch of how the meaning of calls could evolve. Importantly, there is no reason to assume that the 'selection' among different strategies is genetic, especially since there is no evidence of a relevant genetic difference between Tai and Tiwai monkeys; the competition must thus be among strategies that the monkeys use in various communicative encounters, with greater or lesser success.

Several remarks should be added.
–If on average leopard-appropriate reactions yield a higher pay-off than eagle-appropriate reactions, $<R_{trivial}, S_{trivial}>$ won't be a Nash equilibrium any more, not even a weak one: the receiver will have an incentive to use $R_{distinct}$, since as a reaction to $S_{trivial}$ this will lead it to use the superior leopard-appropriate strategy. And once $<R_{distinct}, S_{trivial}>$ becomes prevalent, $<R_{distinct}, S_{distinct}>$ will soon come to dominate.
–If players are allowed to adapt their strategy to the type of the partner in the communication game, it is clear that mutants that play an optimal strategy against non-mutants but play $<R_{distinct}, S_{distinct}>$ against each other will invade a non-mutant, non-discriminating $<R_{trivial}, R_{trivial}>$ population (as the mutants will do strictly better than the non-mutants when they encounter a mutant). This holds even if eagle-appropriate responses are on average better than leopard-appropriate responses.
–We only discussed game-theoretic mechanisms of evolution, but more traditional mechanisms of linguistic re-analysis (used to explain the historical evolution of linguistic forms) could potentially be explored as well. We leave this issue for future research.

5.3.3 *Remaining problems:* krak

❑ *Distribution*

While our data might well be noisy, our current theory leads one to expect that in Tai *krak* on its own (interpreted as $krak_2$, with a leopard meaning) and *hok* on its own should have symmetric distributions, with an overwhelming predominance of leopard-related environments for *krak* and of eagle-related environments for *hok*. But as we noted in Section 2.4.3, there are more cases of 'overapplication' of *krak* than there are for *hok*. We take these data to suggest that *even in Tai krak* sometimes has function of general alarm.

Now we can amend the theory to take this fact into account; after all, we posited that (i) the innate meaning of *krak* is one of general alarm, and in addition (ii) even in Tai, this meaning enters in the derivation of the semantics of *krak-oo*. So it is only a small additional step to posit that bare *krak* is in fact ambiguous in Tai: it can have its meaning of general alarm, and it can also have its strengthened, acquired meaning, which pertains to leopards:

(44) Amendment to the lexicalist theory
–In Tai, unsuffixed *krak* is ambiguous between $krak^1$ and $krak^2$.
–*krakoo* is always interpreted as $krak^1$*-oo*.

(One last consideration that goes in this direction is the fact that *krak* is occasionally found in tree falling situations in the Tai dataset studied in Ouattara et al. 2009a, b: 4% of calls produced in these contexts are *krak* calls.)

❑ *Architectural considerations*

The lexicalist analysis of the Tai vs. Tiwai contrast leaves important questions open: why is *krak* ambiguous between $krak^1$ and $krak^2$? And why is the input to the derivation of the meaning of *krak-oo* the innate meaning $krak^1$ rather than the acquired meaning $krak^2$? On the assumption that there is dialectal variation across Tai vs. Tiwai in the meaning of *krak*, one might expect that in a given dialect *krak* gets the *same* meaning in all of its uses. But this is not what we find: to derive the proper meaning for *krak-oo* in Tai, we are forced to posit an ambiguity. Furthermore, the same ambiguity might be necessary to derive the more fine-grained data which suggest that even in Tai *krak* sometimes has non-leopard-related uses, ones that are not reducible to whatever amount of 'noise' there is in the data for other alarm calls.

We take this complex situation to motivate the development of an alternative analysis.

6 A Pragmatic Analysis

The main difficulty with our lexicalist analysis was that it had to posit an ambiguity (between $krak^1$ and $krak^2$) within the Tai dialect. Here we will develop an alternative analysis in which the ambiguity is not lexical in nature, but rather derives from a general option of pragmatic strengthening. Specifically, we will now assume that all meanings are innate, but that there are rules of competition among calls: all else being equal, the more specific (= logically stronger) call compatible with a situation is preferred. The rule applies maximally, but on Tiwai it yields a nearly contradictory meaning (akin to 'dangerous ground predator', in a situation in which there are no such predators); and for this reason the rule fails to apply.

This line of analysis is in effect based on the notion of *scalar implicatures* developed in recent linguistics (see for instance Chierchia et al., to appear and Schlenker 2012, to appear for recent surveys). In fact, as is the case in recent formal work, we will have to specify in our analysis the *formal alternatives* of the calls of interest. Thus in neo-Gricean analyses of implicatures, one derives from *It's possible that John is the culprit* an inference that one is not in a position to assert that *it's certain that John is the culprit* (on the assumption that *certain* is an alternative to *possible*). Since this inference is not lexically encoded, one fully expects that in some cases *possible* should be used without an implicature – as when one says that *it's possible, and in fact certain, that John is the culprit*. By similar reasoning, we will devise a system in which in Tai *krak* has a (non-contradictory) strengthened meaning akin to *dangerous ground predator;* but we will assume that strengthening need not systematically apply, which will explain why in a few cases *krak* appears to have its broader meaning of general alarm.

Going back to *possible*, the scalar analysis of the *not certain* inference has an additional advantage: it explains why the derived noun *possibility* behaves like the adjective *possible* in allowing for a reading in which the relevant state involves *possibility and certainty*. By contrast, a simple lexical analysis of the inference would predict that *possibility* refers to the *state of being possible but not certain*. In some cases, this would make incorrect predictions. For instance, in the sentence *Whenever there is a possibility that a politician is corrupt, he should resign,* the proposed meaning would fail to entail anything about politicians who are known to be corrupt, contrary to intuition.[23] No

[23]There are simpler cases in which the 'not certain' inference is lifted, as in the following sentence, found in an online forum:

(i) There is always a possibility - in fact a certainty - that people will make bad choices.

problem arises if the words *possible* and *possibility* both involve a notion that does not exclude certainty (and trigger additional pragmatic inferences when competition with the words *certain* and *certainty* are taken into account). By the same token, the meaning of *krak-oo* will naturally be derived from the lexical meaning of *krak*, and for this reason it will *not* have a 'ground predator' component, since the latter is obtained for *krak* by an implicature-like phenomenon. This will explain why in Tai and on Tiwai alike *krak-oo* has a meaning of general alarm.

One point bears mentioning at the outset. While initial studies of implicatures tied them to a theory of communicative rationality (e.g. Grice 1975), far less than full-fledged rationality is needed to obtain a mechanism of competition; all that is needed is a – possibly automatic, unconscious, and non-rational – optimization device by which more informative calls 'suppress' less informative ones. By no means should one assume that a pragmatic analysis of the meaning of some calls commits us to strong claims about the level of rationality achieved by Campbell's monkeys.

6.1 General Ideas

Before we get into technicalities, it is worth sketching our account in general terms. The key pragmatic ideas are informally stated in (45); our basic assumption is that *krak* unambiguous, and always has a meaning of general alert.

(45) a. Pragmatic Scales
{krak, krak-oo, hok, hok-oo} are alternatives to each other

b. Strengthened meanings
For every word *w*, the strengthened version of *w* is written as <u>*w*</u> and its meaning is equivalent to

w and not w_1 *and not* w_2 *and ...*

where w_1, w_2 are alternatives to *w* and are more informative (logical stronger) than *w*.

Let us see informally how this analysis works. First, the competition between *krak* and *hok*/*hok-oo* will have the effect that the general alarm of *krak* will be enriched into *krak and not hok and not hok-oo*. Thus if *hok* has a meaning of aerial predator, the strengthened meaning *krak* will trigger an inference such as: *not involving an aerial predator* (we will refine the meaning of *hok* along the lines of (41)b above, hence this is just a first approximation). Still, this isn't quite enough to give *krak* a strengthened meaning that ends up referring to ground predators. This is where the second competitor, *krak-oo*, enters the picture. Our analysis is in two steps.

–First, we will revise the analysis of the meaning of *-oo* given in (28)/(46)a and replace it with that in (46)b.

(46) **Meaning of *-oo***
a. *Original analysis*
For any root R different from *boom-boom* for any situation s,
$I_{M,s}$(R–oo) = 1 iff in s there is a disturbance that licenses the same attentional state as if $I_{M,s}$(R) = 1, or in other words: in s there is a disturbance that licenses the same attention state as situations s' such that $I_{M,s'}$(R) = 1.

b. *Revised analysis (preliminary)*
For any root R different from *boom-boom* and for any situation s,
$I_{M,s}$(R–oo) = 1 iff in s there is a disturbance which licenses *R* but is not strong among the disturbances that license *R* in situations s' of M.

The reason for this change is that according to (28)/(46)a the meaning of *krak-oo* is strictly weaker than that of *krak*, and thus *krak* could not yield an implicature of the form *not krak-oo*, on pain of contradiction. In (46)b, *-oo* is given the semantic function of an attenuator, but its logical contribution

(accessed on 02/09/2013 on http://forums.welltrainedmind.com/topic/210340-stategovt-regulation-of-hs-good-or-bad/page__st__50) is such that *R-oo* is logically *stronger* than *R*: if *there is a disturbance that is not strong among those that license R*, then *a fortiori there is a disturbance that licenses R* (just not one that is strong!).

–When this revised meaning is taken into account, we will obtain the desired effect once the meaning of *krak* as in (39)a is combined with the implicatures triggered due to competition with both *hok* and *krak-oo*: from the competition with *hok*, we obtain the inference that the disturbance is not related to an aerial predator; and from the competition with *krak-oo,* we get the inference that the disturbance is strong – in other words, *krak* gets the pragmatic meaning of *a disturbance which is strong and which is not related to an aerial predator*.

–We will argue that the optional strengthening *fails* to apply on Tiwai because it would yield a contradiction relative to that environment, since there are no dangerous ground predators, and hence probably no dangerous ground disturbances, on the island.

–This isn't quite the end of the story, however. For given the conjunctive semantics we gave for concatenation in (21), we will incorrectly predict a contradictory meaning for the numerous sequences in which *krak-oo* co-occurs (and often follows) a more urgent alarm call. Consider for instance one of the types of calls listed in (10)e, uttered in an eagle-related situation, and made of a series of *krak-oo,* followed by a series of *hok,* followed again by a series of *krak-oo,* as shown in (47):

(47) K*h*K*

The *hok* component of the sequence is often indicative of an eagle. But our conjunctive semantics will incorrectly yield a meaning roughly similar to: *there is a <u>weak</u> disturbance and there is an aerial predator*. But one would think that the presence of an eagle is certainly not a weak disturbance, hence the meaning might end up being entirely misleading.

A natural solution is to relativize the truth-conditional contribution of meanings to a precise time of utterance, and to the state of mind of the caller. The basic intuition is that the various calls convey information about the caller's state of mind *at the time of that call's utterance*; and this state could well change quickly (and possibly as a result of the call, if the utterer happens to 'discharge' a certain level of alarm as he conveys it to others; the details of such an analysis would need to be worked out, however). On such a view, we avoid assigining misleading truth conditions to (47) because the caller may signal the presence of an eagle at time t while conveying a weak alarm at some later time t+k (or for that matter at some earlier time). Technically, we will add a time parameter to all of our analyses, as is illustrated for *-oo* in (48):

(48) Meaning of *-oo* – Revised Analysis
For any root R different from *boom-boom*, for any situation s, and for any time t,
$I_{M,s,t}$(R–oo) = 1 iff in s at t there is a disturbance which licenses *R* but is not strong among the disturbances that license *R* in situations s' of M.

6.2 Analysis

As announced, we now introduce a time parameter t to make it clear that the meaning of any word corresponds to the utterer's state of information *at the time of utterance t*. As it turns out, however, the time parameter can *replace* the alarm parameter. This is because the function of the alarm parameter was solely to 'count' the number of calls that appeared in a sequence. By adopting a discrete view of the time parameter, one in which if a call is evaluated at time t, the next call is evalute at t+1, we can emulate the effects of the alarm parameter solely with the time parameter. The intuition is straightforward: the longer a monkey calls, the more serious the alarm; and to assess how long a monkey calls, we can certainly rely on the time parameter.

Both the lexical interpretation function I and its extension [[.]] are thus endowed with a time parameter, hence notations such as $I_{M,s,t}(k)$ and $[[k]]^{M,s,t}$ relative to model M, situation s and time t.

❑ *Semantics*

The lexical semantics was informally introduced above and is recapitulated in more precise form in (49), with an explicit relativization to the time of the call and the state of mind of the caller.

(49) Lexical Semantics
For any model M, situation s and time t,
-Roots
a. $I_{M,s,t}$(krak) = 1 iff at t the caller of s is alert to a disturbance
b. $I_{M,s,t}$(hok) = 1 iff at t the caller of s is alert to a disturbance whose source is non-terrestrial
c. $I_{M,s,t}$(boom-boom) = 1 iff at t the caller of s is alert to a disturbance but not of a predator
-Affix
d. for any root R,
$I_{M,s,t}$(R–oo) = 1 iff at t the caller of s is alert to a disturbance that licenses R and isn't strong among disturbances that license *R*.

Given these rules, we can immediately compute the meanings of *krak-oo* and *hok-oo:*

(50) a. $I_{M,s,t}$(krak–oo) = 1 iff at time t the caller of s is alert to a disturbance that licenses *krak* and isn't strong among disturbances that license *krak,*
iff at t time t the caller of s is alert to a disturbance that isn't strong among all disturbances.

b. $I_{M,s,t}$(hok–oo) = 1 iff at time t the caller of s is alert to a disturbance that licenses *hok* and isn't strong among disturbances that license *hok,*
iff at time t the caller of s is alert to a disturbance whose source is non-terrestrial, and which isn't strong among those whose source is non-terrestrial.

As mentioned, in our compositional rules the time parameter now replaces the alarm parameter; since we want to compute the elapsed time between a call and the beginning of the sequence, we assume that the situation parameter s provides information about the time of the first call, so that the equivalent of the 'alarm' level at time t can be computed by considering the value of t-time(s), where *time(s)* is of course the time of the situation s (= the time at the start of the sequence). This is defined in (51), where we have made explicit all parameters:

(51) **Compositional Semantics** (with a time parameter replacing the alarm parameter)
For any model M, situation s (whose time of occurrence is time(s)), time t, word *w*, and string *S*,

a. $[\![w]\!]^{M,s,t} = 1$ iff $I_{M,s,t}(w) = 1$ and the alarm level is[24] at least t-time(s).

b. $[\![w\ S]\!]^{M,s,t} = 1$ iff $[\![w]\!]^{M,s,t} = 1$ and $[\![S]\!]^{M,s,t+1} = 1$

As an example, we can compute the meaning of the sequence *hok krak-oo*, which would have come out as contradictory if we hadn't relativized meanings to times (we assume that time(s) = 0).

(52) $[\![$hok krak-oo$]\!]^{M,s,0} = 1$ iff $[\![$hok$]\!]^{M,s,0} = 1$ and $[\![$krak-oo$]\!]^{M,s,1} = 1$,
iff [$I_{M,s,0}$(hok) = 1 and the alarm level is at least (0-time(s))] and [$I_{M,s,1}$(krak-oo) = 1 and the alarm level is at least 1-time(s)],
iff $I_{M,s,0}$(hok) = 1 and $I_{M,s,1}$(krak-oo) = 1 and the alarm level is at least 1,
iff at time 0 the caller of s is alert to a disturbance whose source is non-terrestrial and at time 1 the caller of s is alert to a disturbance that isn't strong among those that license *krak* and the alarm level is at least 1.

In effect, this two-call sequence has three effects at once: it signals the presence of an aerial disturbance at time 0; it signals that the caller's state of mind has turned to a less serious threat at time 1; and the number of calls provides information about the level of alarm, which should be of at least 1.

For this model to make sense, it should be the case that a Campbell's monkey that is alert to a serious threat – say to an eagle – will not necessarily remain in a state of alertness to that threat, but may go through states of lower and more general alarm. This assumption (which would require some independent motivation) is stated in (53).

(53) **Auxiliary assumption: alertness**
If in a situation s a sequence is triggered at time t by a certain threat, the caller of s might go at times t' > t

[24] We could relativize this further by having: ... the caller of s is aware of an alarm level of at least t-time(s). This further relativization won't bring much, however.

through *lower* states of alarm than what is licensed by the threat, and this might get reflected in the calling sequence.

❑ *Pragmatics*

We already introduced our motivation for positing the set of alternatives in (54)a. The refinement in (54)b, where *Ø* stands for the null string, is intended to allow a sequence *without boom boom* in initial position to yield the inference that one might be in a predation context; for instance, a sequence *krak krak-oo* will evoke the alternative *boom-boom krak krak-oo*. The latter is stronger than the former, hence the pragmatic meaning of *krak krak-oo* will trigger the inference that the speaker is not in a position to assert that the situation is not one of predation, and thus that the situation might be or is one of predation.[25]

(54) **Alternatives**
a. *krak, krak-oo, hok, hok-oo* are alternatives to each other
b. Ø, *boom-boom* are alternatives to each other (hence the *absence* of *boom-boom* gives rise to the inference that one might be in a predation context)

Now the key to obtain the desired results is compute appropriate strengthened meanings; (55) recapitulates with our 'official' notation the informal presentation that was made in (45)b.[26]

(55) **Strengthened meanings**
For every word w, we write as $\underline{w}$ the strengthened version of w, and take its meaning to be given by:
for all situation s and time t,
$[[\underline{w}]]^{M,s,t} = 1$ iff $[[w]]^{M,s,t} = 1$ and for all $w' \in Alt(w)$, if w' entails w, $[[w']]^{M,s,t} = 0$
where Alt(w) is the set of alternatives of w.

Importantly, as is usually assumed in the pragmatics of human language, the relevant notion of entailment is *contextual entailment,* which in the present context can be reduced to entailment given what is known about/holds true in the site of the utterance, assimilated here to the model M of evaluation.[27]

(56) **Contextual entailment**
A word *w' (contextually) entails* a word *w* at site w relative to a model M just in case for every situation s in M, for every time t, if $[[w']]^{M,s,t} = 1$, then $[[w]]^{M,s,t} = 1$.

For future reference, we also define the notion of a (contextual) contradiction in the natural way:

(57) **Contextual contradiction**
A word *w* is a *(contextual) contradiction* relative to a model M just in case for every situation s in M, for every time t, $[[w]]^{M,s,t} = 0$.

Since strengthened meanings are derived by reference to entailment relations among calls, it is worth representing these explicitly. In the representation in (58), a word *w* is above a word *w*' of the class {krak, krak-oo, hok, hok-oo} just in case it is more informative than it.

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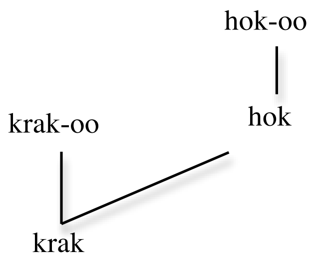
[25] The distinction between 'might be a situation of predation' and 'is a situation of predation' pertains to the difference between primary implicatures (yielding: the speaker is not in a position to assert *boom-boom*, hence the speaker is not in a position to assert that the situation is not one of predation) and secondary implicatures (yielding: the speaker believes that the situation is not one of predation). We disregard this distinction in what follows (see for instance Schlenker 2012 for a recent survey).

[26] In standard neo-Gricean treatments of scalar implicatures (e.g. Horn 1972), the utterance of a sentence *S* implicates the falsity of its stronger alternatives; the intuitive motivation was that for any alternative *S*' stronger than *S*, it would have been more cooperative of the speaker to utter *S*' than *S* if he had believed *S*' to be true. By contrast, in more recent treatments (surveyed for instance in Chierchia et al., to appear, and Schlenker 2012), the utterance of *S* implicates the falsity of any alternative *S*' that is not weaker than *S*. While there appear to be strong empirical arguments for defining implicatures in this second way, it is not entirely clear how it should be derived from a more general theory of rationality or optimization. In the present piece, we stick to the standard neo-Gricean view of implicatures.

[27] See Magri 2009 for an extended argument that implicatures should instead be viewed in a context-independent way.

(58)



Some explanations might be in order.
–Given our semantics for *-oo*, it immediately follows that a modified root *R-oo* always entails the bare root *R*.
–In addition, *hok* – and thus also the stronger *hok-oo* – entails *krak:* if the caller is alert to a disturbance whose source is non-terrestrial, then certainly the caller is alert to a disturbance.
–Are there further entailments? Not if the contribution of *-oo* in *R-oo* ('... weak among the disturbances that license *R*') is understood in a natural, non-intersective way, for instance as: '... is a disturbance in the bottom n%, in terms of threat level, among the disturbances that license *R*'. In particular, without special assumptions, there is no entailment relation between *krak-oo* and *hok-oo*. If *krak-oo* is used, then the caller is alert to a disturbance that counts as weak among all general disturbances; but this need not imply that the caller is alert to a disturbance that counts as weak among all those whose source is non-terrestrial. For instance, if aerial disturbances usually involve eagles, an inter-group encounter might count as a weak disturbance (e.g. in the bottom 10% of aerial threats); but this need not entail that it counts as weak among all the disturbances there are, as many of non-aerial disturbances might be considerably less threatening than eagle encounters (hence an inter-group encounter encounter might *fail* to be in the bottomon 10% of all threats).

Based on the entailment relations in (58), it is easy to compute the strengthened meanings of the calls *krak*, *krak-oo, hok,* and *hok-oo*. (Since we are primarily interested in *krak* and its competitors, we do not repeat here the inferences obtained due to the competition – at the beginning of sequences – between Ø and *boom-boom*.)

(59) On the assumption that the entailment relations represented in (58) are the only ones that hold among {krak, krak-oo, hok, hok-oo}, the strengthened meanings of these calls are:
for every model M, situation s and time t,

a. $[\![\underline{\text{krak-oo}}]\!]^{M,s,t}$ = $[\![\text{krak-oo}]\!]^{M,s,t}$ (since no other call entails *krak-oo*)
= 1 iff at t the caller of s is alert to a disturbance that isn't strong among those that license *krak*,
= 1 iff at t the the caller of s is alert to a disturbance that isn't strong among all disturbances.

b. $[\![\underline{\text{hok-oo}}]\!]^{M,s,t}$ = $[\![\text{hok-oo}]\!]^{M,s,t}$ (since no other call entails *hok-oo*)
= 1 iff at time t the caller of s is alert to a disturbance that isn't strong among those whose source is non-terrestrial (from (50)b).

c. $[\![\underline{\text{hok}}]\!]^{M,s,t}$ = 1 iff $[\![\text{hok}]\!]^{M,s,t}$ = 1 and $[\![\text{hok-oo}]\!]^{M,s,t}$ = 0 (since *hok-oo* entails *hok*)
= 1 iff at t the caller of s is alert to a disturbance whose source is non-terrestrial
but not to a disturbance that is isn't strong among all disturbances whose source is non-terrestrial,
or roughly: = 1 iff **at t the caller of s is alert to a serious aerial disturbance.**

d. $[\![\underline{\text{krak}}]\!]^{M,s,t}$ = 1 iff $[\![\text{krak}]\!]^{M,s,t}$ = 1 and $[\![\text{krak-oo}]\!]^{M,s,t}$ = 0 and $[\![\text{hok}]\!]^{M,s,t}$ = 0 and $[\![\text{hok-oo}]\!]^{M,s,t}$ = 0 (since *krak-oo, hok* and *hok-oo* all entail *krak*)
= 1 iff $[\![\text{krak}]\!]^{M,s,t}$ = 1 and $[\![\text{krak-oo}]\!]^{M,s,t}$ = 0 and $[\![\text{hok}]\!]^{M,s,t}$ = 0 (since *hok* is weaker than *hok-oo*)
= 1 at t the caller of s is alert to a disturbance
but not to one that is weak among all disturbances
and not to one whose source is non-terrestrial

or roughly: = 1 iff at t **the caller of s is alert to a terrestrial disturbance which is serious among all disturbances.**

Some comments are in order.
–Given the entailment relations represented in (58), it is immediate that the strengthened meanings of *krak-oo* and *hok-oo* are identical to their lexical meanings.[28]
–The strengthened meaning of *hok* is predicted to only apply to serious aerial disturbances, whereas *hok-oo* is predicted to apply to non-strong disturbances only. Given the auxiliary assumption in (53), we would expect *hok-oo* to have a broader domain of application than the strengthened meaning of *hok*. As mentioned earlier, in the Tai dataset used by Ouattara et al. 2009a,b, *hok-oo* is systematically used in inter-group encounters, while in such situations *hok* isn't used. But there are also cases in which *hok* has a *broader* distribution than *hok-oo*, as we mentioned in Section 3.2 – a point we leave for future research.
–The strengthened meaning of *krak* is predicted to apply only to serious terrestrial disturbances. On the assumption that strenghtening is applied in most cases (but not always), we obtain two desirable results. First, usually *krak* is used as a leopard alarm call in Tai, as leopards are presumably the most common serious terrestrial disturbance. Second, we also account for the marginal cases in which *krak* is used with a meaning of general alarm. Note that in this respect the situation is not symmetric between *krak* and *hok*: the lexical meaning of *hok* involves non-terrestrial threats, hence with or without strengthening *hok* is predicted *not* to apply to terrestrial threats. By contrast, the lexical meaning of *krak* is unspecific, hence when strengthening fails to be applied non-terrestrial uses can be obtained.

6.3 Tai vs. Tiwai

It remains to account for the difference between Tai and Tiwai in the use of *krak*. Since the lexical meaning of *krak* (general alert) seems to be appropriate for Tiwai, we will argue that there strengthening fails to be applied because it yields a 'contextual contradiction'. Let us develop this idea in greater detail.

In our initial analysis, the distinction was analyzed in lexical terms – with the consequence that the meaning of one call, *krak*, couldn't be entirely innate. In the present analysis, no such hypothesis is needed; to the contrary, we will assume that the *very same linguistic rules apply at the two sites*, but that strengthening is constrained in a way that interacts with the environment. Specifically, strengthening fails to apply in a situtation s of a site M if it yields a contextual contradiction relative to M. In addition, we should posit that strengthening applies otherwise applies in most cases, since we only found few instances of *krak* in non-leopard-related situations in Tai. Both assumptions are stated in (60).

(60) **Strengthening application and strengthening avoidance**
a. If at a site M, for every situation s in M, for every time t, $[\![\underline{w}]\!]^{M, s, t} = 0$, one should interpret an utterance of *w* without strengthening.
b. Otherwise, a word *w* should in most cases be interpreted as $[\![\underline{w}]\!]$.

This natural condition is the source of the difference between Tai and Tiwai. In Tai, the strengthened meaning of *krak* can clearly be used in leopard situations. On Tiwai, things are presumably different: for lack of ground predators, the resulting meaning is contradictory, and for this reason *krak* is always used with its lexical meaning only.

Importantly, *hok* remains unaffected by the rules of strengthening avoidance: the strengthened meaning of *hok* pertains to serious aerial disturbances, as seen in (59)c, and these do exist on Tiwai (in particular because of the existence of eagles). Hence strengthening should be applied; furthermore,

[28] Note that it would be an undesirable result if the strengthened meaning of *krak-oo* implied the falsity of *hok-oo*, as this would predict that when strengthening is applied (which for reasons we'll come to should be *in most cases*), *krak-oo* cannot appear in cases of weak non-terrestrial threat. This does not appear to be correct: as seen in (13) and (27), *krak-oo* appears in almost all triggering environments, including those that involve falling trees or inter-group encounters (in the Tai dataset used in Ouattara et al. 2009a, b; the one exception is the 'cohesion and travel' context, which only triggers *boom boom* in this dataset).

even if it were not, *hok* does not have a general alarm meaning, hence it should always be related to some aerial disturbance.

Needless to say, various refinements could and should be explored. For instance, it might be useful to modify our condition of strengthening avoidance in such a way that it makes reference to 'near-contradictions' rather than 'contradictions'. A (contextual) near-contradiction could be taken to be an expression *E* such that for almost all situations s in M, for almost all times t, $[[E]]^{M,s,t} = 0$).

Importantly, in the present analysis it is predicted that *krak-oo* should have the same meaning at both sites. This is because the one source of variation we have postulated concerns the use of strengthening, which gets blocked when it is contradictory. But as we saw in (59), the strengthened meaning of *krak-oo* is identical to its literal meaning *at both sites,* and thus no source of variation can be found here. Furthermore, the meaning for *krak-oo* obtained from the compositional combination of *krak* and *-oo* seems to be adequate, as it involves a general alarm whose level is relatively weak.

7 Alternative Theories

For clarity, we have focused our discussion on just two theories of the Tai vs. Tiwai distinction. The first one was appealing by its simplicity: *krak* has different meanings at the two sites, and this shows that not all of the call semantics is innate. The second theory was more sophisticated and possibly empirically superior; it posited that *krak* has the same meaning of general alarm at the two sites, and that this meaning can in principle be strengthened by the same pragmatic rule at the two sites – but due to the ecological difference between the two sites (= the absence of ground predator at Tiwai), the strengthening rule yields a contradiction and thus fails to be applied on the island. Still, there are alternative theoretical directions that ought to be explored in future research.

Let us step back to see what should be the main ingredients of a successful account. For clarity, it is useful to classify theories along two main dimensions, pertaining to (i) what the semantic operations provide information about; (ii) what types of informational operations there are, and which are subject to variation.

(i) Situation-sensitive or site-sensitive semantics?
To classify theories with respect to the first dimension, we ask whether the informational content of the various semantic operations is sensitive to (a) the general properties of the site at which the speaker lives (formally analyzed in terms of a model parameter M), or (b) the narrow situation (with an approaching leopard, or an eagle, or a falling tree) in which the calls were uttered (formally, the situation parameter s). Let us illustrate.
–The lexical meanings we postulated in this piece all pertain to the narrow situation of utterance (written as *s*). But different theories could be explored in which this is not so. For instance, a call *w* could be taken to have a meaning akin to: *the most dangerous known predator* relative to M.[29] For this expression to refer in a situation s, there must be a predator in s. But which predator it is will depend on properties of the site at large: hypothetically, the most dangerous predator in Tai might be the leopard, whereas it might the eagle on Tiwai (for lack of leopards!). A theory with rich meanings of this sort could in principle account for the Tai vs. Tiwai contrast on the basis of entirely innate, but site-sensitive meanings. (Note that a meaning akin to *the least dangerous predator* would be site-sensitive in exactly the same way as *the most dangerous predator*; and in the case at hand this lexical entry might yield more adequate results, as leopards are arguably less dangerous than eagles.)
–The pragmatic operation of strengthening used in our pragmatic theory was sensitive to the site of utterance, since we claimed that strengthening fails to apply if it yields a contextually contradictory meaning. Crucially, however, the notion of 'contextual contradiction' was defined *relative to a model M*, i.e. relative to a site. In this way, the prohibition against contradictory strengthenings amounted to an indirect way of taking the site of utterance into account – and this is the reason this second analysis was able to account for the contrast between Tai and Tiwai on the basis of the very same semantics for the two sites.

[29] This possibility was mentioned in discussion by Paul Egré.

(ii) Semantics, pragmatics or cognitive state?
To classify theories along the second dimension, we ask what types of informational operations there are, and which are subject to variation. The information conveyed could be derived from (a) the semantic content of calls [= the literal meaning as encoded by the compositional semantics]; (b) their pragmatic content [= the semantic content together with additional inferences obtained by considering why the speaker uttered one call rather than another one]; and (c) inferences about the cognitive state that led the speaker to say something to begin with. To illustrate, in our lexical theory the action was entirely in the semantic component, which was subject to variation, since we posited a dialectal difference in the meaning of *krak* between Tai and Tiwai (*krak* had a leopard meaning in Tai but not on Tiwai). In our pragmatic theory, the semantics wasn't subject to variation but superfically the pragmatics was, since strengthening could be applied in Tai but not on Tiwai.[30] Finally, in our initial discussion of Diana monkeys, we saw that Tiwai males called differently to leopard growls than their Tai cousins, but that the difference was plausilbly cognitive in nature: not knowing what leopards are, Tiwai males assimilate them to general disturbancies, and display the corresponding calling behavior; neither semantic nor pragmatic variation was needed to explain this difference.[31]

It is worth repeating what will *not* work: a theory in which (1) the informational content of the various elements above is solely dependent on the narrow situation of utterance, and (2) no semantic operation is subject to variation across sites. Given the auxiliary assumption that eagle situations are the same (in relevant respects) in Tai and on Tiwai, such a theory would predict that the same calls are heard in such situations on both sites – and our starting point was precisely that this is empirically incorrect. Thus the conjunction of (1) and (2) appears to be too strong. In our first theory, the conjunction didn't hold because (2) was false: the lexical meaning of *krak* was in fact subjet to variation. In our second theory, (2) was true, but (1) wasn't: meaning strenghtening was indirectly dependent on the site rather than just on the situation of utterance.

8 Conclusion

8.1 The import of a semantic analysis

While we provided a synthetic analysis of the Tai and Tiwai data, and tried to give a fair hearing both to a lexical and to a pragmatic analysis, we could have presented things in a more striking (and more dogmatic) fashion.

Let us start from the Tai data. Superficially, it might appear that *krak* has a leopard-related meaning. But three considerations militate against this conclusion. First, if *krak-oo* is derived from *krak*, and if *-oo* has a constant meaning in all its uses, it is very unlikely that *krak* could have such a narrow meaning given that *krak-oo* is used as a general alarm. Second, this conclusion appears to be supported by the fact that there are a few general alarm uses of *krak*. Third, the pattern this leads to is one which is reminiscent of the divisions of labor between calls in other species: there is a raptor-specific alarm call, and a general alarm call used, among others, for ground predators (as will be recalled, this was the pattern discussed in Wheeler and Fisher 2012). From that perspective, the Tiwai data are a beautiful confirmation of the theory, since there *krak* really *does* have the distribution of a general alarm call.

Importantly, one key ingredient in this analysis was the assumption that *krak-oo* is derived from *krak*: this element of compositionality at the word level turned out to impose constraints on the meaning of *krak* (at least if we want the meaning of *-oo* to be reasonably natural). This, in turn, made

[30] We write 'superficially' because the pragmatic rules were taken to be the same at the two sites: strengthening was taken to apply in most cases unless it yielded a contextual contradiction. It was because of the ecological difference between the two sites that strengthened failed to apply to *krak* on Tiwai.

[31] We could try to posit that the site-sensitivity of the system lies entirely in the decision to utter calls. For instance, *krak* might have a constant meaning of 'high alert' at both sites. Suppose now that leopards are the *most dangerous* predators there are in Tai; monkeys would judge that the 'high alert' is worth using only for the most dangerous predator. On Tiwai, since there is only one predator, they might use it freely. In effect, this is a site-sensitive rule to utter a call, one which implements in non-linguistic terms the kind of site-sensitive meanings we discussed above when raising the possibility that *krak* might mean something like *the most dangerous predator*.

it possible to make it not-too-surprising that at some sites (Tiwai) *krak* is in fact used as a general alarm call.

In this way, there is a subtle interaction between empirical and theory-internal constraints (here: compositionality at the world level). Of course this is just the very beginning of what should become a research program; there is no doubt that as we learn more we will put new theoretical constraints on the model, and we will of course have far more refined data to constrain them.

8.2 Open questions

We conclude with a list of problems for future research.
–The primatology literature is heavily concerned with the distinction between referential and non-referential calls. We have not fully addressed this issue, as it is usually hard to distinguish between, say, an 'eagle' meaning, and a meaning akin to 'threat whose source is aerial'; in fact, we went back and forth between the two types of rules in our own analysis of the meaning of *hok*.
–We excluded *wak* from the present analysis, in part because its delimination from *hok* isn't always obvious. But this should be explored in future research.[32]
–We only discussed male alarm calls, which have the advantage of being easy for researchers to perceive and record. But females have their own repertoire of alarm calls, whose semantics should be studied formally; and its (phonological and semantic) correspondence with male calls should be investigated as well.
–Finally, it should be clear that the *methods* used in the present piece – which are in the end standard methods of formal semantics – could be applied to any number of other instances of primate and non-primate calls (or for that matter communicative gestures).

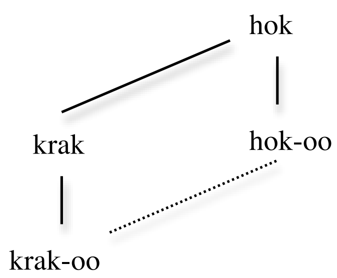
[32] If it is confirmed, the presence of two distinct alarm calls to warn of eagle presence is a bit surprising. One tantalizing possibility is that *wak* referred to a now-defunct aerial predator, which would explain its current similarity with *hok*.

Appendix. An analysis with pragmatic strengthening and no time dependency

The pragmatic analysis developed in Section 6 was based on the idea that *krak* is in competition with *krak-oo* and *hok* (as well as *hok-oo*), which lead to a strengthened meaning <u>*krak*</u> equivalent to *krak and not krak-oo and not hok*, with the rough meaning *the caller is alert to a terrestrial disturbance which is serious among all disturbances*. The key idea was that this strengthening is useful in Tai and primarily singles out ground predators, whereas it is contradictory or near-contradictory on Tiwai (for lack of serious ground threats). But for the theory to work, it was crucial that *krak-oo* should be *more* informative than *krak;* thus we postulated that *-oo* was an attenuative suffix, with *R-oo* meaning roughly: *the caller is alert to a disturbance that isn't strong among those that license R*. This, in turn, led to difficulties for sequences that are indicative of a serious threat (e.g. of an eagle presence), while still containing some instances of *krak-oo*, which has the entailment that the threat is *not* serious. Our solution was to relativize meanings to the precise time and state of mind of the caller, with the assumption that a monkey alert to a given threat may go through phases of less intense alarm than is licensed by the threat. By contrast, in the lexicalist analysis developed in Section 5, *R-oo* had a meaning that was logically *weaker* than that of *R*: *R-oo* roughly meant that there is a disturbance that licenses the same attentional state as *R*. Thus if *hok* means that there is an aerial predator, *hok-oo* meant that one should be in the same attentional state as if there were an aerial predator, with no commitment that there is indeed one – thus one might look up without necessarily being alarmed. For this reason, the lexical meaning of *krak-oo* was entirely non-specific, and in particular it was *not* restricted to weak disturbances; this, in turn, avoided the problem of 'time inconsistency' we got in the second analysis –and hence there was no need to relativize calls to the very millisecond at which they were uttered.

Can we combine the benefits of both analyses? Let us consider the lexical entailments that are plausibly given by our first analysis when we restrict attention to the innate (unspecific) meaning of *krak*, as represented in (61).

(61) Lexical entailments



Since in that initial analysis *R-oo* has a broader range of uses than *R*, *krak* entails *krak-oo* and *hok* entails *hok-oo*. Furthermore, since the analysis was designed to explain why the innate (unspecific) meaning of *krak* (obtained on Tiwai) has a completely general use, it is plausible that *hok* entails *krak*. For the moment, we leave open whether *hok-oo* entails *krak-oo* (we will argue shortly that it should not).

The strengthened meanings we get from (61) with the full lines are given in (62); the rough paraphrases we provide are just initial approximations, as the details depend on the precise lexical entries we will posit.[33]

[33] An alternative research direction would be to appeal to 'higher-order implicatures' (as in Spector 2007) and to posit that *krak* competes with the *strengthened* meaning of *krak-oo*, with the latter meaning 'there is a weak threat'. The difficulty is that with the lexical entailments in (61) (including the dotted line), the strengthened meaning <u>*krak-oo*</u> of *krak-oo* would be something like *krak-oo and not krak and not hok-oo;* and the strengthened meaning of *krak* with that competitor taken into account would yield *krak and not hok and* ***not [krak-oo and not krak and not hok-oo]***. But the conjunct in bold simplifies to ***[(not krak-oo) or krak or hok-oo],*** and due to the disjunct *krak* it turns out to be entirely redundant. [For comparison, in Spector 2007 plurals turned out to have a very weak ('at least one') semantics, but the sentence *Jack saw horses* turned out to have a strengthened meaning of *at least two horses* because the plural *horses* competed with the strengthened meaning of *a horse*. Crucially, however, *a horse* competed with *two horses*, as represented below:

(62) On the assumption that the entailment relations represented by the full lines in (61) are the only ones that hold among {krak, krak-oo, hok, hok-oo}, the strengthened meanings of these calls are:
for every model M and situation s,

a. $[\![\underline{\text{krak-oo}}]\!]^{M,s} = 1$ iff $[\![\text{krak-oo}]\!]^{M,s} = 1$ and $[\![\text{krak}]\!]^{M,s} = 0$ and $[\![\text{hok}]\!]^{M,s} = 0$

b. $[\![\underline{\text{hok-oo}}]\!]^{M,s} = 1$ iff $[\![\text{hok-oo}]\!]^{M,s,t} = 1$ and $[\![\text{hok}]\!]^{M,s} = 0$

c. $[\![\underline{\text{krak}}]\!]^{M,s} = 1$ iff $[\![\text{krak}]\!]^{M,s} = 1$ and $[\![\text{hok}]\!]^{M,s} = 0$

d. $[\![\underline{\text{hok}}]\!]^{M,s} = 1$ iff $[\![\text{hok}]\!]^{M,s} = 1$

Now we could try to emulate the results of our second (pragmatics-based) analysis by arguing in three steps.
Step 1. *krak* is specified for a relatively high level of alarm (while *hok*, as before, refers to disturbances whose source is aerial).
Step 2. The strengthened meaning of *krak*, *<u>krak</u>*, naturally refers to serious non-aerial threats in Tai, namely to leopards.
Step 3. For lack of serious non-aerial threats on Tiwai, the strengthened meaning is never used, and only unstrengthened *krak* occurs.

But this doesn't quite work. The problem lies in Step 1: in our data, *krak* is used for *all* disturbances on Tiwai, including ones (e.g. tree falls) which don't seem to be particularly severe. So for this analysis to work, we must modify Step 1 and assume that there are *two* sources of environment-dependency in the semantics, rather than just one.
(i) As before, strengthened meanings are avoided when they yield contradictions relative to the environment – hence a first source of environment dependency.
(ii) In addition, we must assume that (a) *krak* means something like: there is a threat of at least average intensity given the environment, and that (b) the general level of threat is lower on Tiwai than in Tai (among others due to the absence of ground predators) – hence a second level of environment dependency.
Thus Step 1 is replaced with Step 1', stated informally as follows:

Step 1'. *krak* uttered in environment M means that there is a threat of at least average intensity given M. Threat levels are lower on Tiwai than in Tai, and hence the lexical (unstrengthened) meaning of *krak* has a broader range of uses on Tiwai than in Tai.

With this modified analysis, we can almost derive the results we want:
–In Tai, the strengthened meaning of *krak*, namely *<u>krak</u>*, refers by (62)c to threats of at least average intensity relative to Tai, but only ones to which *hok* cannot apply; hence roughly: to threats of average intensity whose source isn't aerial (or more rigoroulsy: whose source isn't an aerial threat of at least average intensity relative to Tai). This naturally singles out leopards, at least in most cases.
–On Tiwai, for lack of threats whose source is terrestrial, strengthening fails to apply, and *krak* is used with its lexical (unstrengthened) meaning; it thus refers to threats of at least average intensity *relative to Tiwai*. Since the general level of threat is lower on Tiwai than in Tai, *krak* gets applied to threats such as falling trees to which *krak* wouldn't be applied in Tai (even on its unstrengthened meaning).

But there remain two problems.

<u>a horse</u> two horses

| |

horses a horse

As a result, the strengthened meaning of *horses* meant something like: *at least one horse and not <u>a horse</u>*, hence: *at least one horse and not exactly one horse*.We do not have enough alternatives to provide such an analysis in (61), at least not without more sophisticated mechanisms.]

1. First, the distribution of *krak* in Tai can only be explained if strengthening to <u>*krak*</u> (which entails *not hok*) is applied in most cases – for otherwise we would predict many instances of *krak* in all eagle-related contexts, which we don't find. But if *krak* is strengthened to <u>*krak*</u> (when the result isn't contradictory), we would expect that in roughly the same proportion *krak-oo* should be strengthened to <u>*krak-oo*</u>, which entails *not krak*. Without additional assumptions, this might predict that in most cases *krak-oo* is used for threats of less than average level – which doesn't appear to be correct, since *krak-oo* appears in virtually all contexts, including ones that involve leopard growls or eagle shrieks. A natural solution would be to take into account the early parts of a sequence when determining whether strengthening is or isn't contradictory. The idea would be that when *krak-oo* follows a series of *krak*'s or a series of *hok*'s, strengthening to <u>*krak-oo*</u> is blocked because it yields a contradiction *relative to that sequence*. The repercussions of this measure would need to be investigated, however. In particular, one should ask why the same measure wouldn't predict that *krak can* occur in high numbers in non-leopard-related sequences in Tai, as long as it follows a series of *hok*'s, for instance.

2. Second, we must also ensure that *krak-oo* is not strengthened in such a way that it entails *not hok-oo*, for *krak-oo* seems to be used for threats that are aerial as well as non-terrestrial. We might view this as another instance of the first problem mentioned in the preceding paragraph – maybe we just need to find a way to block strengthening of *krak-oo*. Alternatively, we might set up the semantics in such a way that *hok-oo* doesn't entail *krak-oo* – despite the fact that *krak* entails *hok*. This is achieved in the lexical entries we now turn to.

To make the proposed analysis concrete, we define some possible lexical entries for a system which does *not* have the fine-grained time dependency we had in our 'official' model ('one call per time unit').

(63) Lexical Semantics
For any model M and situation s
-Roots
a. $I_{M,s}$(krak) = 1 iff in s there is a disturbance of at least average intensity given the environment M
b. $I_{M,s}$(hok) = 1 iff in s there is a disturbance of at least average intensity given the environment M and its source is terrestrial
c. $I_{M,s}$(boom-boom) = 1 iff in s there is a disturbance but no predator
-Affix
d. for any root R,
$I_{M,s}$(R–oo) = 1 iff $I_{M,s}$(R) = 1 or one should be in the same attentional state as for a prototypical threat licensing (unstrengthened) *R* in M.

It is immediate given (63)a-b that *hok* entails *krak*, as represented in (61). Furthermore, given (63)d *hok* and *krak* entail *hok-oo* and *krak-oo* respectively, since the latter two are weakenings (by way of disjunctions) of the corresponding roots. Finally, the same rule is compatible with a situation in which *hok-oo* does not entail *krak-oo:* the attentional state for a prototypical threat licensing *hok* might be to look up (for an eagle); whereas the attentional state for a protypical threat licensing (unstrengthened) *krak* might be to look around (because unstrengthened *krak* might be used for all sorts of general threats). In this way, we obtain the entailments in (61) represented by the full lines only.

While this model does without fine-grained time dependency, it requires non-trivial assumptions and leaves some problems open – notably the issue of how to block a strengthening of *krak-oo* that would entail *not krak*.

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