Pyow-Hack Revisited:
Two Analyses of Putty-nosed Monkey Alarm Calls*

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Abstract. Male putty-nosed monkeys have two main alarm calls, *pyows* and *hacks*. While *pyows* have a broad distribution suggestive of a general call, *hacks* are often indicative of eagles. In a series of articles, Arnold and Zuberbühler showed that putty-nosed monkeys sometimes produce distinct *pyow-hack* sequences made of a small number of *pyows* followed by a small number of *hacks*; and that these are predictive of group movement. Arnold and Zuberbühler claimed that *pyow-hack* sequences are syntactically combinatorial but not semantically compositional because their meaning can't be derived from the meanings of their component parts. We compare two theories of this phenomenon. One formalizes and modifies the non-compositional theory. The other presents a semantically compositional alternative based on weak meanings for *pyow* ('general alarm') and *hack* ('non-ground movement'), combined with pragmatic principles of competition; a crucial one is an 'Urgency Principle' whereby calls that provide information about the nature/location of a threat must come before calls that don't. Semantically, *pyow-hack* sequences are compatible with any kind of situation involving (moving) aerial predators or (arboreal) movement of the monkeys themselves. But in the former case, *hacks* provide information about the location of a threat, and hence should appear at the beginning of sequences. As a result, *pyow-hack* sequences can only be used for non-threat-related situations involving movement, hence a possible *inference* that they involve group movement. Without adjudicating the debate, we argue that a formal analysis can help clarify competing theories and derive new predictions that might decide between them.

1 Introduction: the puzzle of *pyow-hack* sequences

1.1 Goals

In the last 40 years, primatologists have gathered rich data on the semantic content of alarm calls in diverse groups of monkeys (see Seyfarth et al. 1980a, b for some of the pioneering work, and Zuberbühler 2009 for a survey). While analyses have mostly remained informal, Schlenker et al. 2014 recently argued that the *general methods* of formal semantics could illuminate this empirical domain (although they did not in any way claim that share non-trivial properties with human languages). More precisely, they developed an analysis of male Campbell's monkey alarm calls that crucially hinged on the statement of precise applicability conditions for calls, combined with rules of competition among calls. In this way, two basic tools of contemporary semantics – a theory of truth on the semantic side, and a theory of implicatures on the pragmatic side – were brought to bear on the analysis of monkey calls. This might pave the way for new theories of monkey calls; and this might also offer a new domain of application to linguistic methods.

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In this piece, we apply similar methods to revisit an important debate about the alarm calls of male Putty-nosed monkeys, which like Campbell's monkeys belong to the larger group of cercopitheci.[2] These have two main alarm calls, *pyows* and *hacks*.[3] While *pyows* have a broad distribution suggestive of a general call, *hacks* are often indicative of eagles. In a series of articles, Arnold and Zuberbühler (2006, 2008, 2012, 2013) showed that Putty-nosed monkeys sometimes produce distinct *pyow-hack* sequences made of a small number of *pyows* followed by a small number of *hacks*; and these were shown both in quantitative observational data and in field experiments to be predictive of group movement. For linguists and primatologists alike, a key question raised by these sequences is *whether their meaning is compositionally derived from the meaning of their component parts*. Arnold and Zuberbühler granted that *pyow-hack* sequences are *syntactically combinatorial*, but due to the difference in the use between these sequences and individual *pyows* and *hacks*, they claimed that they are not *semantically compositional*. In this paper, we revisit this issue and compare two broad analyses of this phenomenon. One formalizes and modifies the non-compositional theory. The other presents a semantically compositional alternative based on weak meanings for *pyow* (analyzed as an underspecified call) and *hack* (analyzed with a 'non-ground movement' or 'high arousal' meaning, depending on the analysis), combined with pragmatic principles of competition. As in Schlenker et al. 2014, we make use of an 'Informativity Principle' whereby more informative sequences are preferred to less informative ones. But a crucial innovation is an 'Urgency Principle' which mandates that calls providing information about the nature/location of a threat should come before calls that don't. Semantically, *pyow-hack* sequences are compatible with any kind of situation involving (moving) aerial predators or (arboreal) movement of the monkeys themselves. But in the former situation, *hacks* provide information about the nature/location of a threat, and hence should appear at the beginning of sequences. As a result, *pyow-hack* sequences can only be used for non-risk-related situations involving movement, hence a possible *inference* that they (often) involve group movement. While it is too early to adjudicate this debate, we will argue that a formal analysis of the competing theories can help produce new predictions to be tested in future field studies.

1.2 Initial Data

Data from field experiments give an initial idea of the problem posed by Putty-nosed sequences. While visual predator models and predator vocalizations give rise to the same kind of calling pattern, there is a sharp difference between eagle stimuli and leopard stimuli. Focusing on auditory models as well, and adding as a control calls produced in unknown naturalistic contexts, Arnold and Zuberbühler 2006a summarize the main patterns in (3).

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[2] Cercopitheci are a subgroup of Old World monkeys. Putty-nosed monkeys are officially named *cercopithecus nictitans martini*; Campbell's monkeys are officially named *cercopithecus campbelli campbelli*. According to Guschanski 2013, Putty-nosed monkeys and Campbell's monkeys have a most recent common ancestor that lived approximately 7 million years ago.

[1] They also have a *boom* call, which is produced very differently and is not indicative of alerts; it will play no role in the present discussion.

(1) **Patterns of Putty-nosed responses to auditory models in field experiments (compared with series produced in unknown contexts) [Arnold and Zuberbühler 2006]**

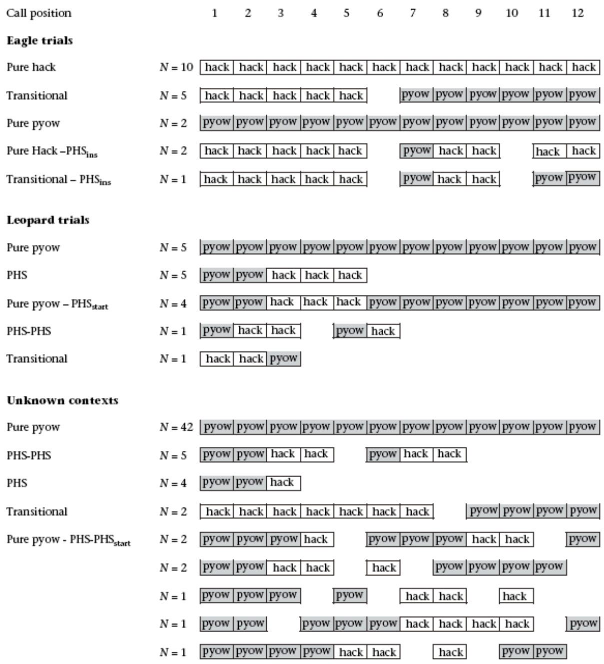


Figure 6. Patterns of call production recorded in eagle and leopard trials and in unknown contexts. PHS: pyow—hack sequence; PHS$_{ins}$: pyow—hack sequence inserted; PHS$_{start}$: pyow—hack sequence at the start of the series. Series produced in unknown contexts are labelled only where they closely resemble calling patterns recorded during experimental trials. Blank spaces represent pauses i.e. intercall intervals of more than the mean + 2SD from the mean for all preceding calls. Where $N > 1$, patterns depicted are generalized. For example, in real transitional call series given in response to eagle stimuli the number of hacks at the beginning of the series ranged from three to eight (median = 5). All calls produced after position 12 are the same as that indicated at position 12.

For clarity, we will use the term *discourse* for any sequence produced in response to an event (this is sometimes referred to as an *episode* in the primatology literature); and we will reserve the term *sentence* for series of calls within a discourse that are delimited by a longer-than-usual interval at the beginning and at the end. The criterion used in Arnold and Zuberbühler 2006 was that such pauses involved and "intercall intervals of more than the mean + 2SD [= standard deviations] from the mean for all preceding calls". With this terminology, Eagle responses are predominantly of two types, as can be seen in (3): pure *hack* discourses, made only of *hacks;* and transitional discourses that start with *hack* sentences and at some point transition to series of *pyow* sentences. Leopard-related discourses primarily include pure *pyow* sentences, but also sentences with a small number of *pyows* followed by a small number of *hacks,* called *pyow-hack sequences* in the literature (with our terminology, they are *pyow-hack sentences*, although we in this case we will often use the more term *pyow-hack sequences*). A few instances of this pattern are also found in Eagle-related contexts. A summary is given in (2).

(2) **Discourse and sentence types**
Notation: P represents a pyow, H a hack. X^+ refers to a repetition of call X and _ represents a pause.

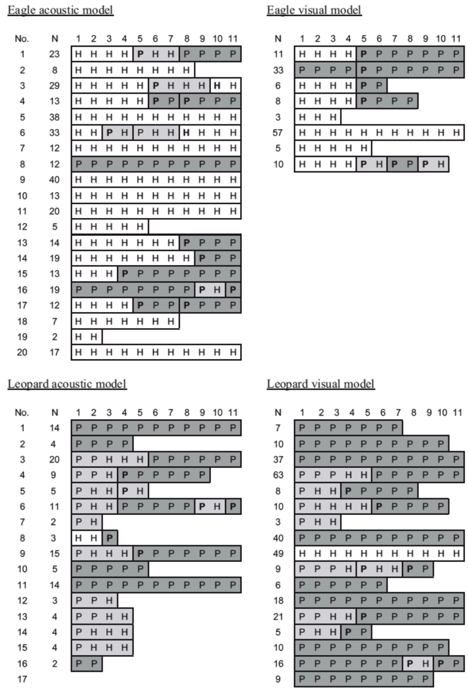
a. *Pyow* series:	P^+ _..._ P^+	(e.g. leopard contexts)
b. *Hack* series:	H^+_..._H^+	(e.g. eagle contexts)
c. Transitional series:	H^+_..._H^+_P^+ _..._P^+	(e.g. eagle contexts)
d. *Pyow-Hack* sequences:	P^+H^+	(trigger group movement)

(these are sentences that include a small number of P's and a small number of H's)

Arnold et al. 2008 provide a more complete dataset, seen in (3); it includes reactions both to auditory and to visual eagle and leopard stimuli, and also to a moving leopard model and to a moving human (which give rise to the same kind of calling pattern). The authors encode inter-sentential pauses (defined here as being above the mean + 3SD of all preceding calls) by writing in bold the beginning of the following sentence.

(3) **Patterns of Putty-nosed responses to auditory models in field experiments (compared with series produced in unknown contexts) [Arnold et al. 2008]**

Fig. 3 Raw data of calling patterns of the first 11 calls given in response to visual and acoustic models of a crowned eagle and a leopard. As alternation in call types was found only during the first 11 calls, we present a maximum of 11 calls. Any additional calls are identical to the 11th call type. Trials are depicted in chronological order. *N*=total number of alarm calls given. Different call series types are indicated by *coloured boxes*: *dark grey* pyow series; *white* hack series; *light grey* pyow–hack sequence; transitional series consist of a series of hacks followed by a series of pyows. Significantly long pauses (mean+3SD of pauses between all preceding calls) between sequences are indicated by marking the first call of the sequence in *bold*



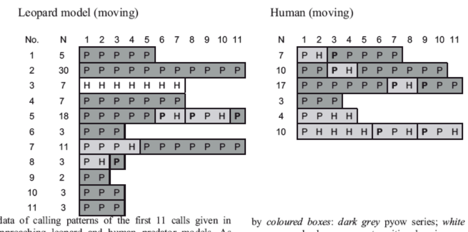
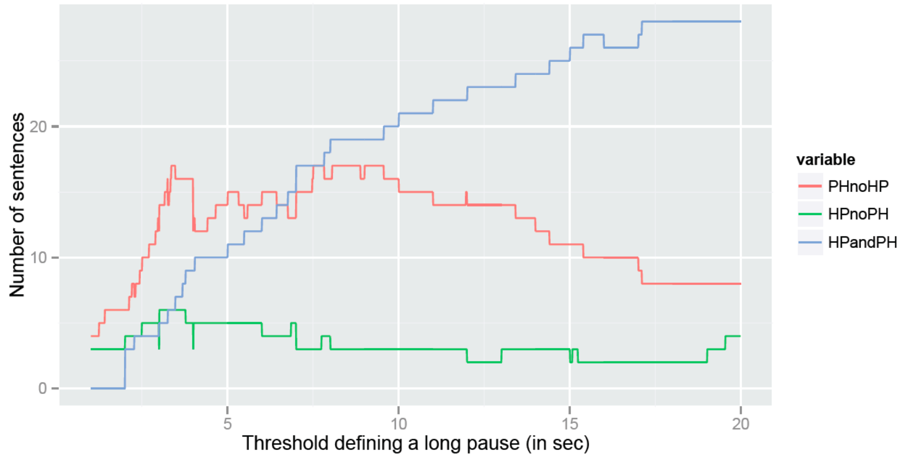


Fig. 4 Raw data of calling patterns of the first 11 calls given in response to approaching leopard and human predator models. As alternation in call types was found only during the first 11 calls, we present a maximum of 11 calls. Any additional calls are identical to the 11th call type. Trials are depicted in chronological order. *N*=total number of alarm calls given. Different call-series types are indicated by *coloured boxes*: *dark grey* pyow series; *white* hack series; *light grey* pyow–hack sequence; transitional series consist of a series of hacks followed by a series of pyows. Significantly long pauses (mean+3SD of pauses between all preceding calls) between sequences are indicated by marking the first call of the sequence in *bold*

It is worth noting that although (1)-(3) contain discourses that start with *hack* sentences and end with *pyow* sentences, there are virtually no *hack-pyow* sentences, i.e. sentences (rather than entire discourses) that concatenate *hacks* followed by *pyows* within the same sentence. This conclusion should be qualified, however: it holds of the data above *using Arnold et al.'s criterion for pauses* (= inter-call intervals of more than the mean +2SD or +3SD from the mean for all preceding calls). In (4), we have represented the number of sentences of different types obtained when we vary the threshold for what counts as an inter-sentential pause (restricting attention to sentences that include both *pyows* and *hacks*). In all cases, we find many more *pyow-hack* sentences than pure *hack-pyow* sentences. In addition, if the threshold is under 5 seconds, we also find few 'mixed' sentences, i.e. ones containing both *pyow-hack* and *hack-pyow* combinations; but this result does not hold when we require that inter-sentential pauses should be above 5 seconds. In sum, pure *pyow-hack* sentences exist no matter which criterion is adopted for inter-sentential pauses, and pure *hack-pyow* sentences are rare; but on some values of the threshold there are significant numbers of sentences with both patterns mixed.

(4) **Number of sentences of different types depending on the threshold adopted for inter-sentential pauses (only sentences containing both *pyows* and *hacks*)**



1.3 Pyow-hack sequences

Arnold and Zuberbühler analyzed the effect of *pyow-hack* sequences in two steps.
–First, Arnold and Zuberbühler 2006 showed that in experimentally triggered Leopard situations (involving leopard growls) and in naturalistic observations, the group of females traveled significantly further when the discourse produced involved at least one *pyow-hack* sequence than when it didn't.
–Second, in field experiments involving natural and synthetic *pyow-hack* sequences, it was shown (i) that natural *pyow-hack* sequences induce group movement far more than either *pyow* or *hack* sequences; that (ii) the same result extends (in weakened form) to synthetic *pyow-hack* sequences, put together from *pyows* and *hacks* given to predator stimuli, as seen in (5); that (iii) keeping the length constant, the precise composition of *pyow-hack* sequences did not seem to affect the distance travelled, as seen in (6). However, (iv) in naturally occurring discourses containing *pyow-hack* sequences, there were indications of a positive relationship between the number of 'pyows' and/or the total number of calls in a *pyow-hack* sequence and the distance travelled by the group, as shown in (7).

(5) **Effect of natural vs. synthetic PH sequences on movement** (Arnold and Zuberbühler 2008)

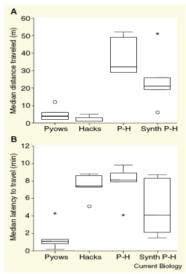


Figure 1. Median distance traveled (A) and median latency to travel (B) after hearing playbacks of different call series by the group's male: 'pyow' series, 'hack' series, natural P–H sequences (P–H), and artificially composed P–H sequences (Synth P–H).
Box plots indicate medians, inter-quartiles and ranges; outliers are indicated by open circles.

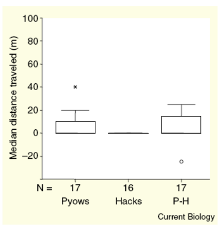


Figure 2. Median distance traveled towards the playback speaker by females after hearing playbacks of 'pyow' series, 'hack' series or P–H sequences by a stranger male.
Box plots indicate medians, inter-quartiles and ranges; outliers are indicated by open circles; extremes are indicated by stars.

(6) **Effect of the composition of PH sequences on movement** (Arnold and Zuberbühler 2012)

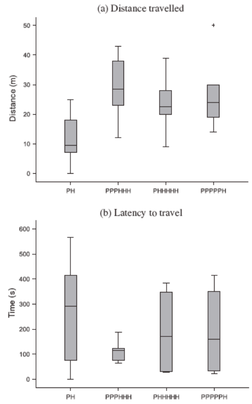


Fig. 4. The effect of different compositions of the P–H sequence on (a) the distance travelled, and (b) the latency to travel during the 20 mins following playbacks.

(7) **Effect on movement of the total number of calls and/or of *pyows* in PH sequences** (Arnold and Zuberbühler 2012)

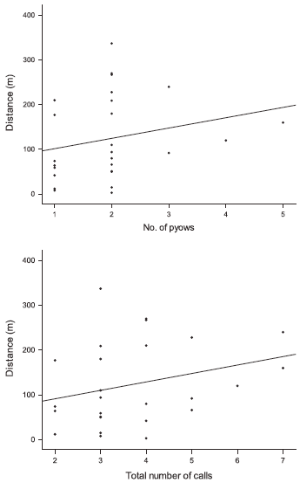


Fig. 3. The relationship between (a) the number of pyows, and (b) the total number of calls in naturally occurring P–H sequences and the distance travelled by the group.

Importantly, 'group movement' in Arnold and Zuberbühler's *pyow-hack* experiments was movement of the females *towards both the speaker and the real position of the male*: the speaker was positioned between the target females and the group's male[4], thus yielding a call that was plausibly produced by the male, even where the target female might have been aware of his general location, as is shown in (8). Importantly, as Arnold and Zuberbühler 2012 note, listeners usually responded to playbacks of different *pyow-hack* sequences by moving *towards the source of the calls*' (our emphasis); group movement can thus be assimilated in this case to an instance of 'group contraction' towards the male.

(8) Arnold and Zuberbühler 2012

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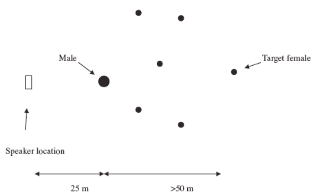

Fig. 2. Experimental setup with speaker location in relation to male, target female and other group members. The observer stayed with the target female and measured her locomotor response to the playback stimulus.

[4] Each group has a single adult male that uses alarm calls, and a varying number of females and juveniles.

2 The Non-Compositional Analysis of *Pyow-Hack* Sequences

2.1 Initial Analysis

Arnold and Zuberbühler have consistently treated *pyow-hack* sequences as being non-compositional; here is for instance one of their recent conclusions:

"our results suggest that the P–H sequence is not compositional in any linguistic sense and if any parallel with human language can be drawn at all, it is with idiomatic phrases such as ''kick the bucket'', in which the meaning of the expression is not derived from the meaning of its constituent words but must be learned as a convention. 'Pyows' and 'hacks' in the context of a P–H sequence resemble free morphemes that have become affixed to each other and merged into a semantic unit (...)." (Arnold and Zuberbühler 2012 p. 308)

As far for individual *pyows* and *hacks*, their position has evolved over the years.
–In Arnold and Zuberbühler 2006, they argued that 'pyows are used primarily when a leopard (*Panthera pardus*) is in the vicinity, and hacks are produced mainly in response to crowned eagles (*Stephanoaetus coronatus*)'.
–In Arnold and Zuberbühler 2013, by contrast, they write (following Arnold and Zuberbühler 2008, Arnold et al. 2011) that "'pyows' function both as alarm calls and also to simply draw attention to the presence and location of the caller", and they add that "these two functions are consistent with one another given that in a predator context, 'pyows' draw listeners toward the location of the caller in order to collectively mob the predator, and to make the predator aware that it has been detected". As for *hacks*, Arnold emphasizes that they are true alarm calls indicative of high arousal, which can be triggered by eagle presence, but by many other phenomena as well; we come back to this point in Section 3.5 (see Arnold and Price, in preparation).

How can we formalize Arnold and Zuberbühler's original insights? We restrict attention to the sentential level, and start by specifying in (9) a particularly simple formal syntax, which definitely falls within the class of so-called 'finite state languages' (e.g. Hopcroft and Ulman 1979). Here + is the *Kleene plus*, and thus P^+ refers to the set of strings made of *P's* alone, H^+ refers to the set of strings made of *H's* alone, and P^+H^+ refers to the set of strings made of an arbitrary number of *P's* followed by an arbitrary number of *H's* (note that the syntax does *not* capture the fact that in P^+H^+ sentences, the numbers involved are small).

(9) **Sentential syntax**
Putty-nosed sentences are generated by the following rules, where $X^+ = \{X^n: n \leq 1\}$:[5]
P^+, H^+, P^+H^+

From the above quote, one might infer that Arnold and Zuberbühler originally had in mind a version of the theory sketched in (10) (at this point the details of the meaning of *pyow* alone and *hack* alone don't matter much). Note that their more recent data argue for a rather different theory, as we will see shortly.

(10) **Non-compositional analysis of *pyow-hack* sequences (1st try)**
a. P = true iff there is an alert
b. H = true iff there is an aerial predator
c. PH = PPH = PHH = ... = PPPPPH = PHHHHH
= true iff the group is moving
d. Sentence-internal composition rule
If *w* is a call and *S* is a string of calls, *wS* is true if and only if *w* is true and *S* is true.

The compositional rule in (10)d specifies that at the sentential level concatenation is interpreted conjunctively. We take this to be a 'null hypothesis' whereby a situation satisfies a sentence just in case it satisfies each of its calls. (If we take entire discourses to provide information about a single stimulus, namely the trigger, this rule could be extended to the interpretation of sequences of sentences; but as we will see below, the series of sentences found in a discourse might well reflect changes in the environment, and if so each sentence should be taken to make a separate claim.)

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[5] + is a modification of the 'Kleene star' *; unlike *, + does not allow for null strings. Thus if S is any set of symbols, S^+ is the set of strings obtained by concatenating any number of symbols from S. When X is a singleton (conventionally identified with its unique element), X^+ is the set of strings of the form X^n for $n \geq 1$.

Several points are problematic in this analysis, however. The first two can easily be addressed with simple refinements of the theory; the last two require more substantial measures.

Problem 1: The rule in (10)c is uneconomical as it stands: it involves in effect a big disjunction of the form *If a sentence has the form* F_1 *or* F_2 *or... or* F_n*, its meaning is ...* . Just listing all these subcases suggests that the theory fails to capture the commonalities among all *pyow-hack* sequences.

Problem 2: More importantly, the analysis in (10) gives rise to undesirable semantic ambiguities. To take the simplest example, it is unclear whether a sentence *PH* should be analyzed as the conjunction of *P* and *H*, interpreted compositionally by way of rule (10)d, or as the 'idiomatic' unit *PH,* interpreted in one fell swoop by rule (10)c. The semantic results are entirely different: with the compositional interpretation, we obtain an aerial predator alert, which is usually *not* associated with group movement; with the non-compositional interpretation, we obtain an indication that the group is moving. Unless we can block the first interpretation, we will not have explained Arnold and Zuberbühler's most striking result, namely the fact that *pyow-hack* sequences trigger group movement.

Problem 3: In addition, the analysis fails to explain why we almost never find discourses that start with a series of *pyows* in response to an eagle stimulus. The problem is that *pyows* are general alarm calls, and thus they should be *true* (i.e. applicable) in Eagle contexts (in fact, we do find them in Eagle contexts, but only at the end of discourses).

Problem 4: Finally, the analysis as stated is somewhat odd because it gives the very same meaning to all sequences that have the same general pattern, such as *P, PP, PPP*, or *H, HH, HHH,* or *PH, PPHH,* etc. While we do not have data on the effect of sentence length on reactions, we saw in (7) that the length of *pyow-hack* sequences (though not their precise composition) has an effect of the distance travelled.

2.2 Improved Analysis

Let us see how we can address these problems while still preserving the spirit of Arnold and Zuberbühler's original non-compositional analysis (again, this will have to be improved to take into account more recent data).

1. To address Problem 1, we will posit lexical rules for entire *sentential patterns*, as in (11). In effect, this means that (this component of) the semantics is insensitive to repetitions of calls.

(11) **Interpretation of *pyow-hack* sequences – revised non-compositional rule**
A maximal string of the form P^+H^+ is true if and only if the group is moving.

2. To address Problem 2, we propose to generalize the format in (11) to *all* sequences, as in (12).

(12) **Non-compositional analysis of *pyow-hack* sequences (2nd try)**
a. A sentence (= maximal string) of the form P^+ is true if and only if there is an alert.
b. A sentence (= maximal string) of the form H^+ is true if and only if there is an aerial predator.
c. A sentence (= maximal string) of the form P^+H^+ is true if and only if the group is moving.

Note that the new theory doesn't have any compositional rules at all at the intra-sentential level. This has the advantage of lifting any kind of ambiguity in the interpretation of sentences. This is so because the rules make reference to *maximal* strings. While the sentence *PPPHH* can be variably analyzed as a single *pyow-hack* string or as a *P* followed by a *pyow-hack* string, the latter analysis would not give rise to an interpretation, since in this context *PPPHH* is a sentence (with longer-than-usual pauses before the first *P* and after the last *H*), but neither the initial *P* nor the rest *PPHH* are sentences (= maximal strings).

An alternative would be to embrace the ambiguities created by (10) (possibly in improved form – e.g. with (10)c replaced by (11)), but to posit a mechanism of ambiguity resolution. For instance, we could postulate that *whenever possible a string is interpreted with an idiomatic* *interpretation*. Since it is not clear what this would follow from, we take the solution in (12) to be slightly more perspicuous.

3. To address Problem 3, we propose to adopt from Schlenker et al. 2014 the device of monkey 'scalar implicatures'.

Briefly, Schlenker et al. postulated in their second (and favored) analysis of Campbell's calls that *krak* is a general alarm call, that *hok* is a non-ground alarm call, and that *krakoo* is a weak alarm call. But they also posited a rule of competition between *krak, krakoo* and *hok*, one according to which *the most informative call* compatible with a given utterance situation *is normally used*. The effect of this 'Informativity Principle' is that an utterance of *krak* usually (but not invariably) gives rise to the inference that *hok* and *krakoo* were not applicable. In the end, this yields the inference that *there was a serious ground alarm*: 'serious' because otherwise *krakoo* would have been used; and 'ground' because otherwise *hok* would have been used.

In the present analysis of Putty-nosed calls, we posit that a P^+ sentence ('there is an alert') competes with an H^+ sentence ('there is an aerial predator'); this is guaranteed by the definition of 'alternatives' in (13). This definition guarantees for instance that *PP* competes with *HH, PPP* with *HHH*, etc. In a second step, the 'Informativity Principle' in (14) specifies that if, as is the case, H^+ is more informative than P^+, then an utterance of P^+ yields the inference that the more informative competitor was not applicable; for instance, an utterance of *PP* will trigger an inference that *HH* wasn't applicable.

(13) **Alternatives**
Any sentence *S'* is an alternative to a sentence *S* if *S* and *S'* are both produced by the syntactic rules of the language, and *S'* can be obtained from *S* by replacing any zero or non-zero number of *P*'s with (the same number of) *H's* and by replacing any zero or non-zero number of *H's* with (the same number of) *P's*.

(14) **Informativity Principle**
If a sentence *S* was uttered and if *S'* is (i) an alternative to *S* (ii) strictly more informative than *S* (i.e. asymmetrically entails *S*), infer that *S'* is false.

One might object that the device of 'scalar implicatures' commits us to overly strong assumptions about a kind of 'theory of mind' in Putty-nosed monkeys. After all, Grice (1975) developed his original theory of implicatures within a framework in which addressees make use of complex principles of conversation to recover the intentions of the speaker. But it should be emphasized, as was done in Schlenker et al. 2014, that far less than a full theory of mind is required by the Informativity Principle. All that is needed is a principle by which a more informative sentence somehow blocks a less informative one. Thus if a sentence *S'* is a an alternative to a sentence *S* and is more informative than it, an utterance of *S* will lead to the inference that the utterance situation likely didn't support *S'*. Knowledge of the Informativity Principle in (14) is sufficient to derive this result, and no theory of mind needs to be posited.

Let us now illustrate in greater detail how the Informativity Principle works. A sentence *PPP* is indicative of an alert and thus can semantically be used in an Eagle context. But it competes with a sentence *HHH*, obtained by replacing each *pyow* with a *hack*. Given our initial semantics in (12), it is immediate that *HHH* is strictly more informative than *PPP*, since if there is an aerial predator, *a fortiori* there is an alert. This result still holds with the refined semantics in (18):
(i) *HHH* is true if and only if there is an aerial predator and the alarm level is at least 3.
(ii) *PPP* is true if and only if there is an alert and the alarm level is at least 3.
It is clear that if (i) is true, (ii) is true, but that the converse need not hold.

As things stand, however, the Informativity Principle makes incorrect predictions when combined with the meanings in (12). The problem is that when competition with H^n is taken into account, a sentence P^n will yield the inference that there is an alert *but not a raptor-related one*. However we saw in (2) that P^+ *does* in fact occur in Eagle-related discourses, just not at the beginning of these discourses. A natural assumption is that the reason we find P^+ sentences at the end of transitional discourses is that the initial trigger for the alarm stops being considered as serious enough to license an H^+ sentence.[6] But this requires a small correction to the meaning we gave for H^+ sentences: they should be indicative of *serious* raptor-related alerts, so that the inference triggered by a P^+ sentence should be that there is an alert but not a serious raptor-related one – which still leaves open the possibility that there is a weak eagle-related alert. The corrected analysis is in (15), with the changes appearing in bold.

(15) **Non-compositional analysis of *pyow-hack* sequences (3rd try)**
a. A sentence of the form P^+ is true if and only if there is an alert.
b. A sentence of the form H^+ is true if and only if there is **a serious raptor-related alert**.
c. A sentence of the form P^+H^+ is true if and only if the group is moving.

With this slightly modified analysis, we can account for the presence of P^+ at the end of some Eagle-related discourses by assuming that the seriousness of an alarm decays over time, as stated in (16).[7]

(16) **Alarm Decay**
The seriousness of an alarm usually decays over time.

4. Finally, to address Problem 4, we still need an additional measure. Schlenker et al. 2014 were faced with a similar problem in their initial analysis of Campbell's calls. For instance, if *krak* is a general alarm call, the three sequences *krak*, *krak krak* and *krak krak krak* should all have the same content. On the basis of observations suggesting that the number of calls per time unit did convey information about the urgency of the threat, they posited in a second step that each Campbell call indiscriminately raised the value of all-purpose alarm parameter. In other words, the precise composition of the sequence did not matter when it came to the effect on the alarm parameter – only the number of calls did. This measure might be appropriate in the case of Putty-nosed calls, but we cannot implement it in a compositional fashion, for the simple reason that the revised analysis is through and through non-compositional. (Nor would it help if it still contained a compositional core, since as we saw in (7) the total number of calls *found in a pyow-hack sequence* has consequences for the distance traveled, and in this case a compositional rule just wouldn't help, since the thrust of the theory is precisely that *pyow-hack* sequences are non-compositional).

We thus resort to the rule sketched in (17):

(17) **General alarm level**
If a sentence contains n calls, it comes with a general alarm level of n.

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[6] An alternative would be to posit that the Informativity Principle does not always apply – which is natural enough for a pragmatic principle. But then we would still have to explain why the Informativity Principle doesn't *equally* fail to apply at the beginning of discourses, which would lead one to expect P^+ sentences in these positions as well.

[7] An alternative would have been to define a semantics for entire discourses rather than sentences, and to take competition principles to apply at the level of whole discourses (i.e. series of sentences). If so, a transitional discourse of the form $H^+\_H^+\_...\_ P^+\_ P^+$ would carry the same semantic content as a pure *hack* discourse of the form $H^+\_H^+\_...\_ H^+\_H^+$ – and thus it would not give rise to the (undesirable) enrichment that *we are not in a raptor-related situation*. Furthermore, we would still preserve the (desirable) consequence that a pure *pyow* discourse of the form $P^+\_...\_P^+$ competes with an analogous discourse containing at least some *hacks*, and is thereby enriched with the assumption that *we are not in a raptor-related situation*. Still, this discourse-based analysis would have to explain why we *fail* to find Eagle-triggered discourses of the form $P^+\_...\_H^+$, with some *pyows* at the beginning. The data could still be derived, but at the price of postulating an additional principle such as the one in (i), which mandates that *hacks* should come before *pyows*.

(i) Urgency Principle
In any discourse, sentences that provide information about the location of a threat should come before those that don't.

As we will see in Section 3.3, we will posit *at the sentential level* a principle very much like (i) in our compositional alternative to Arnold and Zuberbühler's non-compositional treatment. Still, we find an approach based on competition among entire discourses to be undesirable, because it requires meaning computations over very long chunks. For this reason, we find the alternative developed in the text in terms of alarm decay to be more natural.

An important addition is that when *pyow-hack* sequences are uttered, *the distance travelled is an increasing function of the alarm level* – for instance because one might need to travel further to avoid a greater potential threat. The precise nature of the connection is left open by the present theory, and not too much should be read into the expression 'alarm parameter'; what matters is that the analysis provides a semantic reflex of the behavioral role played by sentence length.

If we wish to put together (15) and (17), we must use a richer formalism which takes into account the number of calls that appear in a sentence, as in (18); here too, we indicate the new parts in bold. (As in Schlenker et al. 2014, a sentence of length n requires that the alarm level should be *at least n* rather than *exactly n*; an undesirable consequence of the latter option would be that two sentences of different lengths would contradict each other if they were found in the same discourse[8]).

(18) **Non-compositional analysis of *pyow-hack* sequences (3rd try)**
For any $n \geq 1$, $k \geq 1$ and $< n$,
a. A sentence of the form P^n is true if and only if there is an alert **and the alarm level is at least n.**
b. A sentence of the form H^n is true if and only if there is a serious raptor-related alert **and the alarm level is at least n**.
c. A sentence of the form P^kH^{n-k} is true if and only if the group is moving **and the alarm level is at least n**.

We note that with this modification we still preserve the positive results of our analysis based on scalar implicatures. By the truth conditions in (18)a and (18)b, H^n is still strictly more informative than P^n, and since by (14)a H^n is an alternative to P^n, by (14)b P^n can trigger the inference that H^n is false.

3 A Compositional and Pragmatic Analysis of *Pyow-Hack* Sequences

We take the foregoing analysis to have two major flaws. First, by its very nature it just stipulates the meaning of *pyow-hack* sequences. Second, the *time course* of *pyow-hack* sequences makes it surprising that these should have an idiomatic meaning: they are relatively long, with pauses between calls, which makes it a bit surprising that they should be given a lexical meaning as whole units . (On the initial theory proposed by Arnold and Zuberbühler, it is also surprising that idiomatic expressions should come in a non-stereotyped fashion, with the diversity of forms that *pyow-hack* sequences take – both in terms of length and in terms of patterns of repetition. But we take this worry to have been taken care of by the general claim that repetitions are systematically ignored, except for the computation of the alarm level.)

Our main goal in this section is to develop a compositional alternative to Arnold and Zuberbühler's analysis. In a nutshell, its main components are as follows.
–First, we will take *hacks* to have weak meanings, involving non-ground movement in an initial version of the analysis (further weakened to 'high arousal' in a second version).
–Second, we will take the meaning of some sentences to be enriched by two pragmatic mechanisms instead of just one. As before, we will use an Informativity Principle to explain why P^+ sentences cannot appear at the beginning of Eagle-related discourses. But in addition, we will posit an Urgency Principle according to which, within any sentence, calls that provide information about the nature/location of a threat should come before those that don't. In Eagle-related discourses, this will mandate that *hacks* should come first. For instance, in the first analysis developed below, *pyow-hack* sequence will carry the literal (= semantic) meaning that there is some non-ground movement, but it will also trigger the inference that this is not a threat-related one, for if so the *hacks* should have come first.
–Third, we will assume that world knowledge will yield the further inference that an alert that involves non-ground movement (or high arousal in our second version) but no threat has a good chance of being related to group movement.

Before we develop this somewhat sophisticated analysis, however, we should consider attempts to motivate simpler treatments of *pyow-hack* sequences.

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8 Note that this might not be a very serious problem if different sentences of the same discourse make statements about slightly different situations

3.1 Motivating simple analyses: Collier et al. 2014

Collier et al. 2014 sketch two possible treatments of *pyow-hack* sequences.

(i) First, they offer a possible etymology for the idiomatic meaning of *pyow-hack* sequences according to Arnold and Zuberbühler's analysis: "the sequence first meant 'leopard and eagle' and then, derived from this by implication, 'danger all over'. This, in turn, came to mean 'danger all over, therefore let's go' and finally just 'let's go'." While such an etymological derivation would be desirable, this particular proposal raises worries: if concatenation is interpreted as conjunction, as suggested by the paraphrase *leopard and eagle*, how could a *narrower* meaning than that of *pyow* and *hack* end up being interpreted with what seems to be a *broader* meaning, namely 'danger all over'? If one is to understand this instead as a disjunction (*leopard or eagle)*, the derivation might conceivably go through; but one would need to explain where the disjunctive interpretation comes from. In addition, one would need to explain why the meaning of 'danger all over' licenses the further derivation of 'let's go', whereas the equally general meaning of *pyows* doesn't trigger this inference.[9]

(ii) Second, Collier et al. sketch a compositional alternative as follows:

> one could ascribe much more abstract meanings to 'pyow' and 'hack', such as 'move-on-ground' and 'move-in-air'. When produced on their own, listeners would seek the contextually most relevant and most suitable interpretation of these calls, possibly using similar heuristic processes such as are well established for human communicators in the theory of implicature inferences (...). A default and common implicature would be, in the case of 'pyow', inference to a prototypical danger on the ground, a leopard; and, in the case of 'hack', a prototypical danger in the air, an eagle. Since under this analysis the calls themselves have very abstract meanings, it is possible to analyse pyow-hack sequences as lexical compositions: meanings like 'move-on-ground' and 'move-in-air' combine to a general meaning like 'we move; let's go' since putty-nosed monkeys themselves move both in the tree canopy and, though more rarely, on the ground.

We share with Collier et al. the general strategy of weakening the meaning of *hack* in order to provide a compositional account of *pyow-hack* sequences, and of appealing to implicature-like inferences to enrich the literal meaning predicted by the semantics. But Collier et al. appear to base their analyses on general *relevance* implicatures, whereas we crucially appeal to an Informativity Principle related to *scalar* implicatures, and to an Urgency Principle which does not figure among standard pragmatic principles for human languages. We will claim that under some assumptions our analysis derives the desired results. It is not clear to us that Collier et al.'s analysis does. The conjunction of 'move-on-ground' and 'move-in-air' should yield a quasi-contradiction, since it would not seem that at any moment a creature could both move on the ground and move in the air. Here too, one could attempt to interpret concatenation as disjunction, but again this would raise the question of where this possibility comes from. It might be that the authors mean to compose 'move-on-ground' and 'move-in-air' in a different way, but from their brief sketch the derivation is hard to infer.

3.2 Sentential Syntax and Semantics

- *Syntax*

We start by defining a simple sentential syntax. For reasons we will come to shortly, it is a bit more liberal than the one we posited when we implemented Arnold and Zuberbühler's ideas in (9): in addition to sequences P^+, H^+ and P^+H^+, we also allow for H^+P^+, as stated in (19).

(19) **Sentential syntax (revised)**
Putty-nosed sentences are generated by the following rules:
P^+, H^+, P^+H^+, H^+P^+

- *Semantics*

Since the semantics is now compositional, it can be stated very simply, as in (20).

(20) **Sentential semantics (compositional – without an alarm parameter)**
a. *P* is true if and only if there is an alert
b. *H* is true if and only if there is a **serious** non-ground movement-related **alert**

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[9] An anonymous referee suggests that 'danger all over' might stimulate travel because it signals a higher intensity or urgency of threat, which could only be avoided by leaving the area.

c. If w is any call and S is any sequence,
wS is true if and only if w is true and S is true

The lexical meanings are straightforward, with one exception: as was the case in our non-compositional analysis in (15), we include the part in bold in (20)b with an eye to the fact that in Eagle contexts H^+ can be followed by P^+ sequences, presumably because the seriousness of the alert decays over time[10] (we come back to this point below). Importantly, an *H* call need not provide information about the location of the proximate stimulus, but rather about the source of the threat. This is important because in field experiments auditory stimuli were played from the ground, but still triggered the production of *H* – presumably because eagles usually attack from a non-ground position.

A word should be added by way of motivation. (20)b makes reference to the fact that the threat is (i) non-ground, (ii) serious, and (iii) movement-related. All three categories have some relevance in animal calls. Thus in the analysis developed in Schlenker et al. 2014, the Campbell's root *hok* is specified for non-ground threats, while the distinction between *hok* and *hok-oo* is given by how serious the threat is (with *hok-oo* used for weaker threats). As a result, the bare root *hok* is found n Eagle contexts, while *hok-oo* is found in Eagle contexts as well, but also in inter-group encounters, presumably because these take place in the canopy (Schlenker et al. 2014, graph (27)). In this way, Campbell's calls show the relevance of (i) the ground vs. non-ground distinction, and (ii) the serious vs. non-serious threat distinction. As for property (iii), the movement vs. non-movement distinction, it was argued to be found in a relatively pure form beyond the primate realm, in meerkats. Specifically, Manser and Townsend 2012 describe a meerkat call given specifically to (ground or aerial) animals, but only when they are moving. In other words, there is some independent motivation for the properties combined in the rule in (20)b.

Turning to the compositional rule in (20)c, it simply implements the idea that concatenation is treated as conjunction. But this simplicity comes at a price: the semantics is entirely insensitive to the number of times a call is repeated. As we noted in our discussion of Problem 4 in Section 2.2, in *pyow-hack* sequences total length has a consequence on the hearer's behavior. To address this problem, we can borrow from Schlenker et al. 2014 the device of a parameter whose value gets increased by 1 with each call, as in (21). Importantly, this device will have exactly the same effect as the direct interpretation of sentence length in terms of alarm level in (18): a sentence that's 10-call long will imply that the alarm parameter is at least 10.

(21) **Sentential semantics (compositional – with an alarm parameter)**
For any alarm parameter a ≥ 0,
a. P is $\mathbf{true}_a$ if and only if there is an alert **and the alarm level is at least a**
b. H is $\mathbf{true}_a$ if and only if there is a serious non-ground movement-related alert **and the alarm level is at least a**
c. If w is a any call and S is any sequence,
wS is $\mathbf{true}_a$ if and only if w is $\mathbf{true}_a$ and S is $\boxed{\mathbf{true}_{a+1}}$

The key technical observation is that truth is replaced with 'truth under an alarm parameter', hence the notations $\boldsymbol{true_a}$. At the lexical level in (21)a-b, the parameter gets translated into a feature of the situation of utterance, namely an alarm level, as is intended. At the compositional level in (21)c, the boxed part of the truth conditions guarantees that a sequence *wS* evaluated under an alarm parameter a leads to the evaluation of S under the *raised* parameter a+1.

An example will illustrate the workings of the system. The sentence *PPHH* is of course generated by the syntax in (19). Its truth conditions are given in (22), where we assume that the entire sentence is evaluated with respect to an initial alarm parameter a = 1 (hence the predicate $true_1$ which appears at the beginning of the derivation).

(22) *PPHH* is true_1	iff	*P* is true_1 and *PHH* is true_2	(by (21)c)
	iff	*P* is true_1 and *P* is true_2 and *HH* is true_3	(by (21)c)
	iff	*P* is true_1 and *P* is true_2 and *H* is true_3 and *H* is true_4	(by (21)c)
	iff	there is an alert and there is a serious non-ground movement-related alert and the alarm level is at least 1 and at least 2 and at least 3 and at least 4,	

[10] In Section 3.5, the 'referential' properties of *hack* will be eliminated in favor of a 'high arousal' content, which inherits the 'seriousness' component of the present analysis.

iff there is a serious non-ground movement-related alert and the alarm level is at least 4

In effect, the alarm parameter functions as a counter which keeps track of the number of calls in the sentence, and translates the information into a semantic claim about the situation.

3.3 Pragmatics

The pragmatics is based on two principles, the Urgency Principle, which mandates that calls that provide information about the location of a threat should come first, and the Informativity Principle, which works as in (14). Importantly, we will assume that the Urgency Principle is more 'semantic' (or more 'hard-wired') than the Informativity Principle, in the sense that the latter operates on the information conveyed by sentences in view *both* of their semantics (= literal meaning) and of the effect of the Urgency Principle.

(23) **Urgency Principle**
If a sentence *S* is triggered by a threat and contains calls that convey information about its nature or location, no call that conveys such information should be preceded by any call that doesn't. As a result, if *H's* provide information about a threat, they cannot follow any *P's*.

(24) **Informativity Principle (revised)**
The Informativity Principle in (16) takes into account the information conveyed by the literal (= semantic) meaning of sentences, *combined with* the effects of the Urgency Principle.

❑ *Enrichment by the Urgency Principle*

It will help to consider which calls are applicable in different types of situations. We consider four: Eagle situations, Tree fall situations, Group movement situations, and Leopard situations. In (25), we have represented the results of the semantics together with the Urgency Principle. A star * in front of a sentence type means that it is prohibited due to the combined effects of the semantics and of the Urgency Principle; a checkmark ✔ indicates that a sentence type is not prohibited.

(25) **Semantics + Urgency Principle**

Eagle:	✔H^+	✔H^+P^+	*P^+H^+	✔P^+
Tree fall:	✔H^+	✔H^+P^+	*P^+H^+	✔P^+
Group movement:	✔H^+	✔H^+P^+	**✔P^+H^+**	✔P^+
Leopard:	*H^+	*H^+P^+	***P^+H^+**	✔P^+

–Consider first sentences produced immediately after an Eagle encounter. Semantically, all sentence types are acceptable, since the situation involves an alert as well as a serious non-ground movement-related alert (since eagles are non-ground and moving creatures). But the Urgency Principle blocks a sentence of type P^+H^+*: H* conveys information about the nature and location of the threat, hence it cannot be preceded by *P*.
–The same effects are obtained in Tree fall situations, on the assumption that these do indeed involve relatively serious threats. Note that what counts as 'serious' is left open by the theory, which is underspecified in this respect. On the other hand, it is rather natural to treat Group movement situations differently from Tree fall situations, since the latter but not the former require a rapid reaction and involve a threat.[11]
–In Group movement contexts, all sentence types can presumably be used. Since Putty-nosed monkeys are arboreal, group movement presumably involves non-ground movement, and the event is important enough to count as 'serious' – hence the *H* call ('serious non-ground movement-related alert') can be used; and it is immediate that *P*, which is entirely general, can be as well. Furthermore, because no call provides information about the nature or location of a *threat,* the Urgency Principle does not prohibit the use of any sentence type.

[11] There is arguably evidence for this categorization in Campbell's monkeys. Schlenker et al. 2014 cite naturalistic data collected by Ouattara in which contexts of 'Cohesion and travel' gave rise to the production of some *booms* and no *kraks* at all, whereas Tree fall situations gave rise to the production of *booms*, but also of numerous *kraks* (graph (27) in Schlenker et al. 2014). This can be explained if Tree fall situations but not Cohesion and travel situations involve a threat, which triggers the production of *kraks*.

–Finally, in standard Leopard contexts, no non-ground movement-related alert is involved, and hence *the H call cannot be used*, which only leaves the P^+ sentence type as a possibility. Importantly, if field experiments were conducted with leopards in the canopy, we might expect on the present theory that the *H* call *could* be used in those contexts.[12]

If we stopped here, we would already be in a position to explain why *pyow-hack* sequences convey information about Group movement, since within the restricted set of situations we consider, *if* a P^+H^+ sentence is used, then one is in a Group movement context. Still, the results illustrated in (25) might be insufficient in at least two respects. First, (25) fails to explain why we only infrequently find pure P^+ sentences right after an Eagle stimulus. Second, (25) fails to explain why *only* P^+H^+ sentences are used to trigger Group movement, since according to this analysis *all* sentence types are appropriate in a Group movement context; by contrast, the data in (6) above show a *distinct* role of *pyow-hack* sequences in triggering group movement.

❑ *Further Enrichment by the Informativity Principle*

If we wish to derive the (potential) result that sentences other than *pyow-hack* sequences are *not* indicative of group movement, we can do so using the Informativity Principle, as can be seen in (26).

(26) **[Semantics + Urgency Principle] + Scalar Principle**

Eagle:	✔H^+	✔H^+P^+	*P^+H^+	#P^+
Tree fall:	✔H^+	✔H^+P^+	*P^+H^+	#P^+
Group movement:	#H^+	#H^+P^+	$\boxed{✔\mathbf{P^+H^+}}$	#P^+
Leopard:	*H^+	*H^+P^+	***P^+H^+**	✔P^+

We start from the table in (25), but add pound signs # in front of sentence types that are prohibited by the Informativity Principle.
–Clearly, P^+ sentences are the least informative of all – which can be seen in (25) by reading the table vertically and noticing that P^+ has checkmarks on all lines whereas other sentence types only have checkmarks on some lines. As a result, in all situations in which other sentence types are permissible according to (25), P^+ is blocked by the Informativity Principle, hence the three pound signs that appear in the last column in (26).
–Crucially, the same reasoning rules out H^+ and H^+P^+ sentences in Group movement situations: while they have the same literal (= semantic) content as P^+H^+, unlike it they fail to be enriched by the Urgency Principle, and hence are strictly less informative than P^+H^+ (this can be seen by reading once again the table in (25) vertically, and noticing that P^+H^+ has a checkmark in a single type of situations, namely Group movement ones, whereas H^+ and H^+P^+ have other checkmarks in addition). Since P^+H^+ can be used in group movement situations, it outcompetes other sequences and ends up being the *only* appropriate sentence in that environment. Given the restricted set of situations we consider, this now explains why a P^+H^+ can give rise to a Group movement inference.

We can now state our reasoning a bit more generally:

(27) **Derivation of the use of *pyow-hack* sequences**

a. P^+H^+ sentences can be in violation of the Urgency Principle, and hence their literal meaning is enriched by it. As a result, they are only applicable in situations in which there is a serious non-ground movement-related alert but not one which is due to a threat.

b. Unlike P^+H^+ sentences, H^+ and H^+P^+ cannot be in violation of the Urgency Principle, and thus their meaning is not enriched by it. As a result, they are strictly less informative than P^+H^+ sentences, and the Informativity Principle guarantees that in situations in which there is a serious non-ground movement-related alert but not one which is not due to a threat, only P^+H^+ can be used.

c. (a) can explain why P^+H^+ sentences trigger group movement if it is supplemented with the following principle of world knowledge:

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[12] Note that leopards that climb on trees certainly *attack* from a non-ground position. For this reason, this case is not the 'mirror image' of that of eagles that are on the ground. As we discuss in fn. 13, eagles on the ground still attack by flying, hence from a non-ground position. Certainly leopards that pursue their prey in a tree don't first climb down to attack it.

Assumption about World Knowledge: The most common situations in which there is a serious non-ground movement-related alert but not one which is due to a threat involve group movement.

While we could posit in the Assumption about World Knowledge in (27)c that *all* the situations that satisfy the underlined part involve group movement, this might be overkill; for if *most* such situations involve group movement, it might be advantageous for female Putty-nosed monkeys that hear the relevant call to behave as if this were indeed the event that caused the call.

Several remarks should be made to conclude this section.

–First, the meaning we posited for *H* is very underspecified – and this is crucial to guarantee that it can be indicative of events that are as diverse as the group's (non-ground) movement and an eagle's (non-ground) appearance (see Arnold and Zuberbühler 2013 for discussion). It is also temporally underspecified: in the case of an eagle's appearance, the call might be used to convey information about an event that just happened or is still happening. In the case of group movement, the call might be used to *initiate* the relevant non-ground movement. This means that some amount of temporal inference is needed on the part of the hearers to 'complete' the message conveyed by the call.

–Second, the present analysis makes several non-trivial predictions about more intricate situations that could arise naturally or in field experiments.
(i) Some primatologists have systematically investigated the simultaneous effect of predator nature *and* location on calling behavior. Thus Cäsar et al. 2013 study Titi monkey calling sequences in situations that involve (a) a cat model on the ground, (b) a cat model in the canopy, (c) a raptor model on the ground, and (d) a raptor model in the canopy. Interestingly, they show that these four situations give rise to four distinct types of calling sequences. Given the meaning we posited for *H* ('serious non-ground movement-related alert), we might expect that in 'Leopard in the canopy' situations, *H* calls might be used – a case which hasn't been tested yet. Still, as we noted before, our analysis must be flexible enough to account for the fact that *H* is produced as a reaction to Eagle stimuli *which were played from the ground*; as we mentioned above, this can be understood on the assumption that eagles normally attack from a non-ground position.[13]

(ii) Importantly, the informational content we obtained for *pyow-hack* sequences in (27)a is weaker than 'group movement'. Thus the present theory leads one to expect that *pyow-hack* sequences might be used for some non-threatening events that involve non-ground movement (but are 'serious' enough to license the use of the *H* call). One might for instance ask whether group encounters might trigger the use of *pyow-hack* sequences – if indeed such group encounters are not seen as threats.[14]

–Third, on a methodological level, it should be emphasized that although our *semantics* is compositional, our *pragmatics* relies on global comparison of sentences, since both the Urgency Principle and the Informativity Principle enrich the meaning of a sentence *S* by considering *other* sentences than *S*.

–Lastly, it should be emphasized that our definition of the Informativity Principle in (14) and (24) is standard, and in particular that it is similar to the principle used in the pragmatic analysis of Campbell's monkey calls developed in Schlenker et al. 2014. In both cases, *asymmetric entailment* lies at the heart of the principle. What is less standard is the fact that in the present case the input to the Informativity Principle is not a set of lexical meanings, but rather a set of sentential meanings

[13] Schlenker et al. 2014 discuss several potential analyses of the data in Cäsar et al. 2013; and in one of these analyses they argue that world knowledge grounds, 'Raptor on the ground' situations *should* in fact license the use of non-ground-related calls, because raptors on the ground still present non-ground threats: if they attack, they will likely do so by flying. In the present analysis, the same argument must be extended to Putty-nosed monkeys in the case of Eagle stimuli played from the ground. (See Shultz and Thomsett 2007 for eagle hunting strategies in the Tai forest. Note that an additional possibility is that an Eagle stimulus played on the ground is still indicative of a non-ground threat because eagles occasionally hunt in pairs, with one of them flying.)
[14] Thanks to James Fuller for relevant discussions.

enriched by the Urgency Principle. Still, the fact that the Informativity Principle is often 'fed' by other sources of information is not new. In English, if I tell you: 'I have a high school degree', you will infer that this is probably the highest degree I have. While this can be derived on the basis of the Informativity Principle by considering the alternatives {*I have a high school degree, I have a BA, I have an MA, I have a PhD*}, one needs a further principle to the effect that the first member of the set is asymmetrically entailed by the others; lexical knowledge is certainly not enough to derive this inference.[15] In other words, what is special about the present account is not so much the fact that the Informativity Principle takes enriched meanings as input, but rather the fact that the Urgency Principle is used to enriched the relevant meanings.

3.4 Discourse Effects

We noted in Section 2.2 that in Eagle-related situations P^+ sentences occur at the end but not at the beginning of discourses. In our discussion of the non-compositional analysis, this fact was captured by giving H^+ sentences a meaning of 'serious raptor-related alert', and by assuming that a general principle of 'alarm decay' makes the alert less serious as the trigger becomes more distant. While the Informativity Principle blocks the use of P^+ sentences in case an alert is still considered serious, when this is no longer the case P^+ sentences can in fact appear. The same strategy can be adapted to the compositional theory. First, we already defined lexical semantics for H in (20)b and (21)b in such a way that it involves a *serious* non-ground movement-related alert. Second, we can simply assume that the principle of Alarm Decay in (16) continues to hold. As in the non-compositional theory, the Informativity Principle will ensure that H^+ (or possibly H^+P^+) sentences outcompete P^+ sentences soon after an Eagle stimulus has appeared; but when the threat becomes less serious because it is temporally more distant, the H call might stop being appropriate, with the result that P^+ sentences could be used.

3.5 A non-referential alternative

Arnold and Zuberbühler 2013 significantly revise their earlier findings on the use of *hacks*:

> In previous studies, male putty-nosed monkeys most often responded to the simulated presence of crowned eagles with a series 'hack' or 'transitional' series, and to the simulated presence of leopards with 'pyow' series (...) . However, in the present study, 'hack/transitional' series were recorded at least equally often in a variety of other contexts as well, including to nonpredatory disturbances and the calls of neighboring males. 'Pyow' series were given in an even wider range of contexts, often overlapping with those that elicited 'hack' and 'transitional' series, and most often without any apparent cause at all. In experiments designed to mimic natural situations in which the group male called in response to an audible disturbance, or situations in which listeners had no information about the cause of calls, we found that listeners spent more time looking upwards in trials that consisted of playbacks of 'hacks' alone than those in which 'hacks' were preceded by acoustically simulated disturbances indicating a likely cause of the calls. In response to 'pyows' alone, listeners spent more time looking toward the presumed location of the caller than when 'pyows', similarly, appeared to be given in response to simulated disturbances.

As Kate Arnold has often emphasized, it might be that *pyows* are multifunctional, attention-getting calls, and *hacks* are alarm or 'high arousal' calls (Arnold and Zuberbühler 2013, Arnold and Price, in preparation). Since we have used the term 'alarm' very liberally in the rest of this piece, namely to refer to any event worth calling attention to, we can formalize this non-referential semantics as in (28) (where the parts in bold highlight the changes with respect to (21); note that we have not modified our analysis of P, whose meaning is as general as before).

(28) **A non-referential semantics (compositional – with an alarm parameter)**
For any alarm parameter $a \geq 0$,
a. P is true$_a$ if and only if there is an alert and the alarm level is at least a

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[15] Similarly, Schlenker 2012 argues that it is only after contextual assumptions are taken into account that the Informativity Principle can be applied to the {some, every/all} scale. In other words, contextual knowledge is needed to explain why *Some applicants got in* implicates that *Not all applicants got in*. In a nutshell, the argument is that *Every/All NP* does *not* come with a *lexical* requirement that *NP* has a non-vacuous extension. And it is only when the latter assumption is satisfied that *Every/All NP VP* asymmetrically entails *Some NP VP* (see Schlenker 2012, Section 4.2.2 for a detailed argument).

b. H is true$_a$ if and only if there is **an alert causing high arousal** and the alarm level is at least a
c. If w is a any call and S is any sequence,
wS is true$_a$ if and only if w is true$_a$ and S is true$_{a+1}$

It is immediate that, as before, H is strictly more informative than P, and thus the Informativity Principle could apply to the new system in the same way as to the old one. In fact, with appropriate assumptions, some of the same predictions could be derived from the new system. To get to that point, it might help to think intuitively of the non-referential analysis as replacing notions of 'high movement' in physical space with 'high degree of emotional movement' in internal cognition. On the assumption (based on world knowledge) that 'high arousal' is often caused by things that are high in physical space – notably eagles and tree falls – we will get partly similar results to those had before.

This exercise can be completed in two steps: first, we must connect 'high arousal' to ecological conditions that can be assessed in observation or in field experiments; second, we must revise the statement of the Urgency Principle (as noted, the Informativity Principle will apply in the same way to the new and to the old system).

(i) Assumptions connecting high arousal to ecological conditions
We will assume that high arousal is caused by eagles but not by leopards, as the latter are unlikely to capture a monkey once detected. In addition, high arousal might be caused by events in the monkeys' immediate environment, which is usually arboreal. As a result, there will generally be a close correspondence between events that would have licensed H on the old and the new theory.

(ii) Revision of the Urgency Principle
In our compositional (and referential) theory, the Urgency Principle prescribed that in a sentence triggered by a threat, calls that provide information about the nature/location of the threat must come before those that don't. This idea won't be applicable to the new, non-referential theory. But a different intuition might yield the same result: in case a *hack* is produced as a reaction to a threat, it is an emotive *reaction* and should thus come before other calls – and hence before *pyow*. This is stated in (29):

(29) **Urgency Principle (non-referential version)**
If a sentence S is triggered by a threat, arousal-based calls in it must come before non-arousal based calls.

The intuition is that in a *pyow-hack* sequence, which is indicative of group movement, the speaker might be in a high arousal state (and thus produce a *hack*) because of its intention to move and/or of an incoming event. Whereas in Eagle contexts a *hack* is produced as a reaction to a scary event and thus has to be produced first. Importantly, the revised Urgency Principle does not simply stipulate that *hacks* always come before *pyows*. Rather, it is only when *hacks* appear in a sentence *triggered by a threat* that they must come first. This, in turn, makes intuitive sense since in this case the high arousal calls are produced as an automatic reaction to a potentially life-threatening situation.

With these two assumptions, we can replicate in an arousal-based system most of the results of our compositional analysis, though of course there is now the possibility that *hacks* will occasionally be triggered by ground events or by events that don't involve movement (though if our assumptions are correct this will be rare).

While it is too early to adjudicate among these analyses, this exercise in theory comparison highlights an important *methodological point*: within the semantic/pragmatic framework we assume, the precise semantic content may be open to much discussion, as different contents might interact with world knowledge/ecological conditions to yield the same kinds of consequences. On the other hand, entailment relations and their consequences for pragmatic principles turn out to be very crucial indeed. In fact, in the case we just discussed, entailment relations and pragmatic principles were almost constant across the referential theory and the arousal-based alternative, despite the fact that they postulated rather different lexical contents for the calls.

3.6 Further directions

The analyses developed in this section were compatible with the view that a *pyow-hack* sequence as a whole is triggered by a single event. One could explore further analyses in which *each component of a* pyow-hack *sequence reflects a separate triggering event.* In particular, we could adopt a 'dynamic view' of meaning (e.g. Stalnaker 1978), one on which each call affects the initial belief state of the hearer *as modified by the preceding calls*. This would make it possible to compose calls by an operation of 'dynamic conjunction' in such a way that *PH* and *HP* do *not* end up having the same meaning. A possible analysis of our data could be developed along the following lines.
–First, we posit that belief states come with a focal center of attention, which by default is the speaker, but may shift depending on the information obtained from the environment or from calls.
–Second, we posit that a *pyow* indicates that 'the focal center of attention triggers an alert', while a *hack* indicates that 'the focal center of attention triggers a serious non-ground movement-related alert' (in a referential analysis) or that 'the focal center of attention triggers high arousal' (in an arousal-based analysis).
–Third, as a result: (a) when a series of *pyows* are uttered on their own, they lead to the inference that the default center of attention, namely the speaker, requires attention – hence the 'attention-getting' function of *pyows;* (b) when a series of *hacks* are uttered on their own, they convey the information that the focal center triggers a serious non-ground movement-related alert or triggers high arousal – which usually licenses the inference that the focal center is a raptor; (c) when a *pyow-hack* sequence is uttered, the *pyow* part leads to a belief state in which the speaker is the focal center and requires attention, and then the *hack* part leads to the inference that *this very same focal center* involves non-ground movement or requires urgent attention.
The details are non-trivial to implement, however, and they require a more complex semantic machinery, based on dynamic notions; hence we leave this theoretical possibility for future research.

4 Conclusions

Several conclusions can be drawn from the present study.

(i) Arnold and Zuberbühler's original theory cannot be implemented without elaboration. In particular, adding an idiomatic component to *pyow-hack* sequences doesn't suffice to explain why such sequences couldn't *also* have a non-idiomatic meaning. A natural solution is to give an idiomatic meaning to *all* sentences, with the general claim that the core semantics (excluding alarm level) is insensitive to repetitions.

(ii) It is possible to provide a compositional alternative to Arnold and Zuberbühler's theory, one in which *pyow* and *hack* have constant meanings in all their uses, in line with the general strategy (but not the particular theoretical choices) of Collier et al. 2014. This might be desirable in view of the relatively slow time course of *pyow-hack* sequences. However this theory made heavy use of two pragmatic principles: an Informativity Principle which found much use in human languages, and also in Schlenker et al.'s (2014) study of Campbell's calls; and an Urgency Principle which might seem natural but was tailor-made for the present data.

(iii) The compositional theory may but need not be based on referential notions. As we saw, there is a version of the analysis on which *hack* is a high arousal call; assumptions about world knowledge are then used to explain why high arousal is in many cases connected to eagle presence.

(iv) The main competing theories make rather different predictions about cases that have not been tested so far. In particular, Arnold and Zuberbühler's non-compositional theory predicts that *pyow-hack* sequences should be narrowly connected to group movement. By contrast, the compositional alternatives had no choice but to predict a somewhat broader meaning for *pyow-hack* sequences, and to rely on world knowledge to ensure that, *in most cases*, *pyow-hack* sequences would be triggered by and interpreted as ongoing or imminent group movement. For instance, our first compositional theory would lead one to expect that in situations that involve non-threatening non-ground movement, *pyow-*

hack sequences might be found as well. This remains to be tested.

(v) Comparison with other primate species would be instructive on at least two levels.
–First, from the perspective of our compositional theory, one would want to know whether there is *independent motivation* for the lexical meanings we posited and, more importantly, for the pragmatic principles we relied on. The Informativity Principle was already used for Campbell's monkeys in Schlenker et al. 2014, and it seems to be necessary in any system in which a general alarm call *fails* to be used when a more specific call is available. The Urgency Principle is more controversial, and data from further species might strengthen or weaken its plausibility.
–Second, it would be of particular interest to investigate related species that plausibly have counterparts of *pyows* and *hacks,* in order to determine whether they also have *pyow-hack* sequences. This is arguably the case, for instance, of Blue monkeys, which share a common ancestor with Putty-nosed monkeys approximately 2.5 million years ago (Guschanski et al. 2013), and have close acoustic counterparts of *pyows* and of *hacks*[17] (Fuller 2013; James Fuller, p.c.). From the perspective of a non-compositional theory, a comparative study might make it possible to date (in evolutionary terms) the appearance of *pyow-hack* sequences.[18] From the perspective of a compositional theory, it might make it possible to make a fine-grained prediction: if, say, Blue monkeys have versions of *pyows* and of *hacks,* one would expect that either (i) they display comparable *pyow-hack* sequences as well, or (ii) the lexical semantics of the calls and/or the pragmatic principles they are subject to are not quite the same as in Putty-nosed monkeys. One interesting possibility would be to synthesize Blue monkey versions of *pyow-hack* sequences to test whether they too trigger group movement.

While our positive conclusions are very modest at this point, we believe that the use of formal models will greatly help in clarifying possible theories and deriving competing predictions in the future.

[17] Blue monkey counterparts of *hacks* are called *kas* in the literature.

[18] Besides being intrinsically interesting, this exercise in monkey 'evolutionary linguistics' might make it possible to reconstruct the ancestral meanings of *pyow* and *hack* that gave rise to the non-compositional meaning of *pyow-hack* sequences – which might explain the current meaning of these sequences. (To see a rather distant analogy, consider the idiomatic expression *to give short shrift* to something, meaning: *to give little attention to it*. To understand how it arose, it is useful to know that *shrift* used to refer to a brief period of time allowed to a condemned prisoner to make a confession.)

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