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Coordinating social action: a primer for the cross-species investigation of communicative repair

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Human joint action is inherently cooperative, manifested in the collaborative efforts of participants to minimize communicative trouble through interactive repair. Although interactive repair requires sophisticated cognitive abilities, it can be dissected into basic building blocks shared with non-human animal species. A review of the primate literature shows that interactionally contingent signal sequences are at least common among species of non-human great apes, suggesting a gradual evolution of repair. To pioneer a cross-species assessment of repair this paper aims at (i) identifying necessary precursors of human interactive repair; (ii) proposing a coding framework for its comparative study in humans and non-human species; and (iii) using this framework to analyse examples of interactions of humans (adults/children) and non-human great apes. We hope this paper will serve as a primer for cross-species comparisons of communicative breakdowns and how they are repaired.

This article is part of the theme issue 'Revisiting the human 'interaction engine': comparative approaches to social action coordination'.

1. Introduction

Social interaction in primates is fast-paced, multi-modal and highly contingent [1–3]. Used in noisy and uncertain environments characterized by fission–fusion social dynamics [4], primate communication systems must provide various ways to deal with hitches, breakdowns and other forms of communicative trouble. Human joint action, for instance, is well-known for its system of communicative repair. Repair refers to the process by which communicative trouble is fixed, by a producer who repeats, elaborates or otherwise modifies a troubled utterance either by their own initiative (self-initiated repair, [5]) or in response to a recipient's prompt or explicit signalling of misunderstanding (other-initiated repair, [6]). Across the world's languages, other-initiated repair is extremely frequent, with no 5 min of conversation going by without the occurrence of repair [7]. The fact that, everywhere in the world, disruptions of interaction are resolved so frequently bears witness to the cooperative nature of human interaction [8,9], emphasizing the pivotal role of repair in human joint action coordination. Indeed, repair has been tacitly assumed to be part of the human 'interaction engine' [8]—an assemblage of presumably human-unique cognitive and behavioural features that fuel cooperation in its most complex forms.

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However, repair is not an isolated phenomenon: it can be dissected into a number of cognitive and behavioural building blocks that are found, to various degrees and in various forms, across non-human communication systems. These include the ability to monitor and modify one's own communicative behaviour; to communicate in temporally contingent turns; to keep track of others' responses or their absence; to repeat or elaborate one's signals in response to communicative trouble; and finally, the ability to signal trouble or request its resolution.

A large array of comparative research on non-human primates has now demonstrated that at least some of the basic building blocks of repair are present beyond humans (e.g. turn-taking, [10–12] and flexible signalling via repetition and elaboration, [10,11]). Such findings suggest a potential evolutionary continuum of repair, insofar as the sophisticated cognitive processes constituting it (i.e. reasoning about asymmetries in understanding and taking these into account in redoings) probably rely on a set of ancient and more basic interactional resources. In a step towards unpacking this evolutionary continuum, this paper proposes a species-agnostic comparative approach to study the empirical phenomena of repair, including self-initiated repair via self-correction, persistence and elaboration, and other-initiated repair. We group any such forms of communicative repair (regardless of their interactional contingency) under the shorthand label REDOINGS—a generic, non-teleological term that is sufficiently precise to permit comparability while allowing us to track variation in key aspects like form and function, sequential structure and interactional contingency.

Specifically, we propose a coding framework for the sequential analysis of redoings that enables cross-species comparison. We use this framework to review existing evidence and exemplify it by analysing examples of video-recorded interactions of chimpanzees, bonobos and humans. In doing so, we hope our research framework can be used as a template to produce systematic, comparative data on joint action in non-human animal species, and contribute towards stronger empirical foundations for the cross-species investigation of communicative behaviour [12–14]. With more comparative evidence on interactional structures across species, we may be able to trace evolutionary continuities in strategies for the resolution of communicative trouble and to assess the extent to which repair may be part of a human-unique foundation on which language has evolved [8].

We see a productive methodological convergence between approaches rooted in conversation analysis [15–17] and primate interaction [3,12,18]; a possibility that has been hinted at sporadically [19–21] but only now, with the increasing availability of rich multi-modal interactional data, is coming within reach. To make visible the convergence between disciplines, we start by defining and unpacking human concepts of repair (self-initiated repair and other-initiated repair), to then translate them into species-agnostic phenomena that can be studied in non-linguistic species like non-human great apes. This convergence enables a fruitful interdisciplinary approach that privileges the study of joint action as an interactional achievement [22] over a focus on specialized semantic properties or hypothesized cognitive capacities [14,19,23,24].

2. Empirical manifestations of repair in humans

Repair is ubiquitous in human conversation and has been recognized as a key empirical model to investigate how individuals negotiate shared understanding [25–27]. The publicly observable correlates of repair are reflective of underlying processes like self-monitoring and other-monitoring, and of cooperative motivations like joint commitment [28] and an orientation to understanding and sharing intentions [29]. Repair is one of the things that can make communication especially robust to noise, perturbations and breakdowns. We provide cross-cultural examples of repair from human interaction in the electronic supplementary material, Examples S3.1–S3.6.

One common form of repair observed in human interaction is *self-initiated repair* [30]. This form of repair typically happens mid-stream during a communicative turn or just after its possible completion (prior to the recipient's next turn) and can involve various forms of modification (e.g. by inserting, deleting, searching, aborting, parenthesizing, recycling, reformatting or reordering material [31]). Self-initiated repair is often taken to be indicative of a self-monitoring process [32] and may be carried out to correct performance errors or to adjust formulations for appropriateness. It may, but *need not* be interactionally contingent on others' behaviour (or lack of it). Versions of self-initiated repair that are not obviously interactionally contingent on another's behaviour are here referred to as self-corrections (see also [33]) to mark their putative non-social nature. However, in social settings, such a distinction quickly becomes fuzzy, especially in non-linguistic species. We thus acknowledge that, with empirical data on social interaction, it is not always possible to commit to such a categorical distinction. Another important clarification is that, in conversation analysis, self-initiated repair is technically known as *self-initiated self-repair*, making visible a distinction with *other-initiated self-repair*. The term *self-repair* in these related phenomena captures the capacity of correcting, repeating or elaborating one's previous utterance, but it does not specify whether or not the repair was initiated (prompted) by self or by other.

Other-initiated repair is an explicitly interactive form of repair (sometimes referred to as interactive repair) [34]. Here, a producer (self) repairs a prior turn in response to a recipient (other) signalling a problem in perceiving or understanding a prior turn. Different from self-initiated repair, here a recipient actively invites the signaller to repair a previous utterance. This means that other-initiated repair can be characterized in terms of three interactional turns: a recipient's repair initiation at turn 'T0', related to another's prior turn 'T−1' and the supply of a repair solution in the next turn 'T+1' [35]. Further rounds of initiation and resolution may ensue if the solution turns out insufficient, e.g. T−1, $T0_{a,b,c}$, $T+1_{a,b,c}$ etc. As we will see below, this tripartite sequential structure also offers a straightforward template to characterize interactionally contingent self-initiated repair, if we conceive of the T0 as an abstract position in which the absence of a (desired) response functions as a prompt to produce some form of redoing (e.g. a repetition or a modified utterance) in position T+1.

Interactive repair requires flexible collaborative action by signaller and recipient. It involves individuals monitoring discrepancies in attention, knowledge and understanding, and signalling such discrepancies when communicative trouble arises. It also requires coordination, suspending the current line of action to cooperatively resolve the trouble. Because of this, it has been described as one of the places where theories of mind come to the surface [7].

Table 1. Building blocks of communicative repair. (The different forms of repair are on the columns, and the building blocks on the rows.)

	self-initiated repair			
	self-correction	persistence	elaboration	interactive repair
self-monitoring	✓	✓	✓	✓
interactional contingency	✘	✓	✓	✓
flexibility in signalling	✘	✘	✓	✓
other-prompting	✘	✘	✘	✓

In humans, several ways of initiating interactive repair can be distinguished based on how participants signal the trouble and contribute towards its resolution [6,7]. Open requests like 'huh?' or 'what?' signal a problem but leave open what or where it is; they typically invite repetition or elaboration. Restricted requests like 'by whom?' query a specific part of the prior turn; they invite repetition or clarification. Restricted offers like 'you mean Alex?' also restrict the problem space but at the same time offer a potential solution; they invite confirmation or clarification. Many expressions used to initiate repair rely on conventionalized resources that are in part language-specific, though open request initiators like 'huh?' appear to show cross-linguistic commonalities [36].

Repair initiations can use multiple communicative modalities (see also Holler [37]). Non-verbal other-initiations of repair can include a marked absence of response by recipients ('freeze-looks' in both spoken and signed languages, see [38–41]), body movements [42], puzzled facial expressions (e.g. eye-widening, [43]), head tilting [43] and gestures (e.g. cupping one's hand behind the ear [44]). The repair initiations' form and selection can thus be adapted to different kinds of communicative trouble, including matters of perceptual disruption and asymmetries in attention, knowledge or understanding.

The sequential structure of interactive repair appears to be universal across human cultures [36], and children are exposed to it from early on, with one study finding that about 50% of English infant–initiated interactions (aged 11–18 months) resulted in other-initiated repairs by carers [45]. Already in their first year of life, young children design their gestural communication in ways that show awareness of others' attentional states [46] and may engage in self-initiated repair (e.g. by repeating or revising communicative acts unprompted), revealing a degree of self-monitoring [47,48]. Their full participation in other-initiated repair sequences takes more time to develop. While children first produce repairs in response to other-initiations, by the age of 3 years, they appear to also be able to convey their own lack of understanding and ask for clarification, starting (in English) with open requests like 'huh?' and 'what?' [49–51].

To sum up, interactive repair in humans: (i) relies on an ability to redo or revise communicative turns as well as to invite others to repair their previous utterance, (ii) consists of distinctive sequential elements, (iii) employs a range of interactional practices, (iv) is used in a pragmatically universal way, and (v) has a piecemeal ontogenetic emergence. Given that repair in humans consists of these distinct features, the possibility arises that some of them were already in place before the emergence of language, providing a promising arena for comparative research with differently disposed agents like young infants or non-human primates [52].

3. From redoings to interactive repair: basic building blocks

Although repair in human interaction has all the looks of a highly complex, cognitively sophisticated, linguistically scaffolded process, it is possible to dissect it into constitutive elements that can be traced in communication systems across species. In doing so, we aim for a bottom-up gradualist approach rather than a top-down all-or-nothing stance [53], distinguishing observed communicative behaviour from assumed cognitive capacities and intentional states.

We can illustrate this methodological choice using the topic of intentionality. One might argue that flexible and complex social interaction—of the type exhibited in interactive repair—requires capacities for intention attribution or mind-reading that are possibly unique to humans [54,55]. This might lead us to not expect interactive repair in animals apparently lacking such capacities (but see [56]), and indeed, to date, there appear to be no reports of interactive repair in communication systems other than human language. However, this all-or-nothing mode of reasoning easily obscures possible continuities that might shed light on evolutionary precursors. Here we take a more pluralistic, bottom-up approach that focuses on the interactive character of social cognition [57,58]. We do this partly out of methodological necessity: while people readily attribute intentions to themselves and others [59] and adults can be hypothetically induced to deal with to seven recursive orders of intentionality [60,61], studying intention attribution and perspective taking in prelinguistic children and non-human species is much harder and always more indirect [23,56,62]. We do it also out of empirical prudence, reflecting a data-driven move in studies of primate communication from all too categorical statements about inabilities to reason about mental states [63] to much more gradient conceptions of communication as a coordinated activity involving pragmatic inference [64,65]. With this perspective in mind we can ask: what are the cognitive and behavioural building blocks of interactive repair, and which possible continuities do they show across animal communication systems? Our review of repair in human interaction has furnished us with a number of key elements that we can now enumerate. Specifically, we discuss four key building blocks necessary for the different behavioural (empirically observable) forms of repair (table 1).

The first is SELF-MONITORING—the ability to monitor and adjust the performance of one's own signalling behaviour. As we noted earlier, self-initiated repair in the form of self-correction [30] implies at least a degree of self-monitoring in the form of an action-perception feedback loop [32]. Evidence for the importance of such a monitoring loop in vocally communicating species comes from perturbation of auditory feedback, which is causally linked to stuttering (syllable-level repetition) in both humans and zebra finches [66,67]. While self-initiated repair may be directed simply at increasing fluency [68], it does often occur in social contexts and can display a form of flexibility in signalling (recipient-dependent modification) [69]. In humans, it is frequently linked to the process of recipient design [70] and shows evidence of people finely tuning the delivery and content of talk to their developing understanding of recipients' knowledge and attention [71]. Among non-human primates, self-initiated repair appears to exist in great apes (see review below), as well as in captive populations of siamang gibbons and agile gibbons, who appear to be able to interrupt and self-repair their performance mid-stream when they run into trouble during great-call duetting sequences with other conspecifics [33,72].

The case of social duetting leads us to the second building block: INTERACTIONAL CONTINGENCY, the ability to temporally coordinate communicative behaviour (turn-taking) and engage into action sequencing (sequence organization). The capacity to organize communicative behaviour on a turn-by-turn basis is widespread among social animals [73,74] and provides a key infrastructure for coordinated action [75]. In human interaction, turn-taking appears in proto-form before the advent of speech, first emerging around the age of 11–18 months and further developing until the age of 2–3 years [45,76,77], growing into a finely tuned system of social accountability that governs who talks when [75] and how to deal with overlaps [70,78]. However, simple forms of temporal coordination of turns may have convergently developed in several vocally communicating species [79,80]; for instance, in marmosets, it can be described in terms of arousal-based coupled oscillator dynamics [81]. Comparative work on turn-taking across species is still rare [73], but recent work specifies flexibility, participation, timing and response types as key aspects to look at [74]. Besides temporal organization, interactional contingency also implies a form of sequence organization: the ability to normatively organize turns in relation to each other, for instance in adjacency pairs such as question-answer sequences in humans [82], or request and offer sequences in orangutans [83]. While this may seem deeply intertwined with complex language, some of the most widespread types of paired communicative actions, such as greetings or recruitments [84–87], may indeed have structural equivalents also in other species of great apes [17,18,88–90], as well as in other animal species outside the primate realm [22].

While interactional contingency enables persistence (the repetition of behaviour in the absence of a desired response), the third building block that is often featured in redoings is FLEXIBILITY IN SIGNALLING. This enables elaboration, or the modification and amplification of communicative behaviour depending on other's attentional states and/or knowledge. Persistence and elaboration can be thought of as social forms of self-initiated repair, as they are united in being interactionally contingent operations on one's own communicative behaviour. They differ in their sequential organization compared to self-corrections: whereas self-corrections typically involve signaller's unprompted initiative in correcting and resuming of a performance mid-stream, persistence and elaboration rely on a recipient's noticeable lack of (or undesired) response. As such, persistence and elaboration are usually interpreted as providing evidence for intentional (goal-driven) communication and some degree of awareness of others' attentional states or knowledge [2,10,91]. Human interaction offers direct structural analogues: both persistence and elaboration are common and occur in the course of pursuing responses [92,93] and dealing with communicative trouble [70,94]. Persistence and elaboration are also common in non-human primates, for which we present a more detailed review in the following section.

The fourth and final key building block to consider is OTHER-PROMPTING. Other-prompting involves a recipient (other) signalling communicative trouble such that the producer (self) can repair it by repeating or modifying the troublesome turn, interactively distributing the repair process over participants. This represents possibly the most cognitively demanding element: a recipient has to recognize that a communicative signal was produced; has to monitor their own grasp of it and conclude it is insufficient; has to recognize the producer is a conspecific (or agent) who may be able and willing to repeat or modify the troublesome turn; and has to signal this state of affairs, prompting the other to repair (a behaviour observed in other-initiated repair). It is likely that this requires the kind of behavioural and cognitive means usually associated with ostensive-inferential communication [7,54,59]. However, even here, there is some room for gradience and continuity. For instance, other-initiations of repair in human interaction range from highly explicit and cooperative formats (offering a candidate understanding for confirmation) to more implicit displays of trouble, like puzzlement or a freeze-look ([38], see for an example the electronic supplementary material, S3.3, including Example S3.3)—the latter shading into the lack of response that can occasion persistence or elaboration across species. Other-initiated repair can thus be seen to build on the full range of key building blocks outlined above: self-monitoring, interactional contingency (with the repair solution made relevant by a display of trouble), flexibility in signalling (with the repair solution usually being a recipient-designed redoing of the trouble-source turn) and other-prompting (with the other prompting the need for repair). This means an individual engaging in other-initiated repair would also be expected to be able to engage in more basic versions of repair, such as self-correction, persistence and elaboration.

In summary, the interactive, empirically observable patterns of repair are based on a number of constitutive building blocks (table 1): (i) the ability to self-monitor, (ii) the temporal and sequential coordination that leads to interactional contingency, (iii) the flexibility of communicative behaviour (recipient-dependent usage), and (iv) the possibility of prompting. Cumulatively, these elements build the complex coordinative process of interactive repair, and separately, they feed into simpler types of redoings that can be empirically observed across disparate animal communication systems.

We now review the evidence of the extent to which such building blocks are attested in our closest living relatives, the non-human primates. Such parallels will provide an interesting testbed from which to generate hypotheses about the gradual evolution of repair behaviour, with phylogenetic as well as ontogenetic layers of varying complexity [52].

4. Elements of redoings in non-human primates

As we saw above, redoings of communicative signals can involve communicative persistence or elaboration, contingent on the lack of a (desired) response. This means they bear a structural similarity to self-initiated repair sequences in which communicative actions are redone or reformulated based on another participant's behaviour [7].

The first studies exploring interactionally contingent redoings in interactions of captive great apes focused on contexts of food begging by apes towards human experimenters. Researchers assumed that great apes would deploy different communicative strategies depending on the type of communicative failure: (i) recipients do not react at all and (ii) recipients do react, but not in the appropriate way (i.e. satisfying the signaller's social goal). Leavens *et al*. [10] showed that chimpanzees persist in signalling and often elaborate the communicative attempt by using multiple signals if the communicative attempt for an unreachable food reward failed. Similarly, in orangutans, communication was reliant on the type of communicative failure [11]. They adopted cross-modal tactics to achieve communicative goals, by repeating signals if the signals were partially understood (i.e. receiving an undesired item) and substituting gesture types and sensory modalities if signals were completely ignored (i.e. not receiving any food item). This set-up was again expanded by exposing bonobos to food items held out of reach by experimenters of varying familiarity [95]. Results showed that, when communication failed, the subjects were more likely to elaborate to new signals when interacting with unfamiliar experimenters, and to repeat the same gestures with familiar experimenters. Thus, experimental evidence on great apes suggests that they are able to deal with communicative trouble via persistence and elaboration, and even adjust these attempts according to recipient familiarity.

However, several critiques have highlighted that human experimenter-dependent paradigms may not accurately reflect strategies that apes employ in naturalistic interactions with conspecifics. Focusing on interactions between zoo-housed chimpanzees, Liebal *et al*. [96] showed that the majority of sequences of gestures consisted of repetitions of the same gestures, which was considered a consequence of the recipient's lack of responsiveness, and thus interpreted as persistence. However, Genty *et al*. [97] could not replicate this effect of responsiveness for gesture sequences produced by gorillas, and instead suggested that sequences function to adjust the tempo and nature of interaction. In a study on wild chimpanzees, Hobaiter & Byrne [98] reconciled these seemingly contradictory findings by distinguishing 'rapid-fire' sequences from 'gesture bouts' in which series of gestures were interspersed by response waiting (inter-event intervals of greater than 1 s). While rapid-fire sequences were not contingent on receiver responses, gesture bouts were mostly preceded by a signal that lacked a response from the receiver. Replicating the central findings of Cartmill & Byrne [11] in naturalistic interactions, Roberts *et al*. [91] showed that wild chimpanzees repeated gestures when a response partially matched their goal, but substituted the original gesture when a response was incongruent.

Overall, this and further evidence from species as diverse as coral reef fishes, birds and monkeys [99–101] suggests that interactionally contingent redoings of signals may indeed act as a repair mechanism in the face of communication breakdowns. Although elaboration of signalling occurs less frequently than persistence, it constitutes more solid evidence of other-monitoring (and flexibility in signalling), since the change of the signal type seems to require more voluntary control and is less likely to be purely emotionally driven (e.g. in chimpanzees, repetitions of a 'pant-grunt' from a subordinate individual could be explained by high arousal levels, but if the signaller 'presents the genitals' to the presumed recipient after the 'pant-grunt', this may indicate a higher level of cognitive control [2,102,103]).

Evidence for behaviours resembling communicative repair in non-human *vocal* communication is more scarce. In recipient-focused field experiments that confronted wild chimpanzees with snake models [104,105], individuals reportedly persisted in calling until their apparent goal of warning others about perceived danger was met (see also another experiment on monkeys, where female Diana monkeys presumably 'correct' males' incongruent predator alarm calls [106]). Similarly, an observational study on predator alarm calls in Thomas langurs reported that males persisted until each group member alarm-called at least once [107]. Work on social duetting in captive siamang gibbons has presented some evidence of self-initiated repair in an interactive context, with signallers terminating and restarting broken call sequences [33], and even some cases in a newly formed siamang pair where such repair seemed contingent on lack of response or displays of trouble [72]. For instance, in 17 out of 252 observed great-call sequences (some of them stimulated by playback), the female 'hesitated markedly in mid-performance' [72, p. 376]. The male then either 'repeated his double boom cue' (13 instances) or 'initiated a brief exchange of barks with the female' (four instances), after which the female continued, completing the sequence (ibid). More systematic studies are needed on whether vocal redoings can indeed be interactively negotiated.

In summary, given that non-human primates repeat and elaborate gestural signals in communicative interactions with others, there is evidence that they engage in self-initiated repair via self-monitoring, interactional contingency as well as flexible signalling (table 1). However, it is poorly understood whether they would also engage in interactive repair, where the recipient initiates repair and the original signaller provides the resolution. Thus, current data only show that non-human primates engage in self-initiated repair via repetitions and elaboration, but not whether any form of interactive repair exists beyond humans.

5. A species-agnostic primer for the cross-species study of repair

As becomes clear from the previous sections, generic methods for recovery from communicative trouble are widespread in animal communication systems. Although repair may be more common than we think in non-human primates and other animal species, most research has focused on signallers [108,109], without taking into account recipient responses. This is problematic for the study of repair, because repair needs to be studied as a social phenomenon, with a specific focus on the interactive exchange between signaller and recipient. In cooperative interaction, one set of such methods involves signals being repeated or elaborated [10,33,110], often until they result in the signaller's desired behaviour by the recipient. A sequential perspective on this kind of interaction can help us distinguish a number of key dimensions. Let us define a simple scheme in which we refer to sequential positions as T−1, T0 and T+1 and as the involved parties as 'self' and 'other', or A and B (figure 1).

Given these elements, we can look at how A's moves at positions T−1 and T+1 relate to each other, yielding a contrast

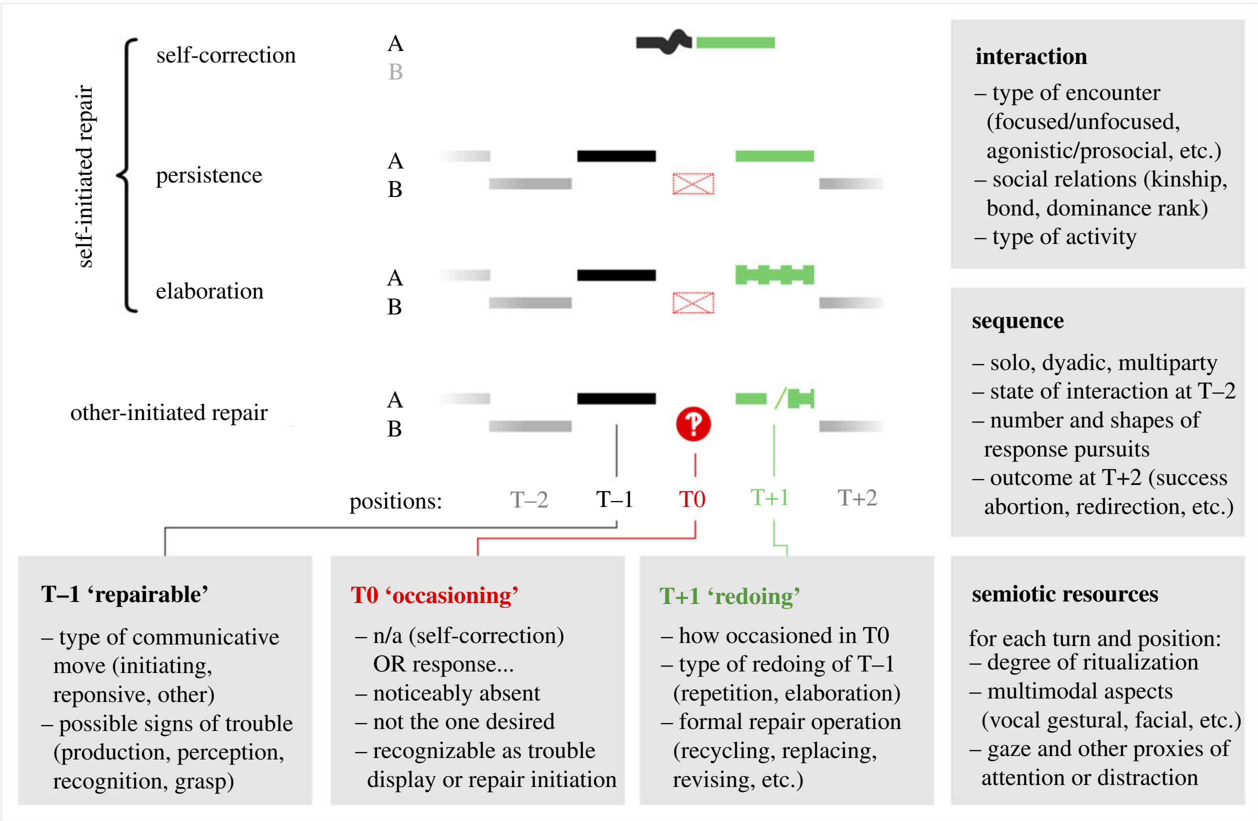

Figure 1. Key elements of a cross-species framework for analysing and comparing redoings.

between persistence (simple repetition) versus elaboration (elaborated, substituted or upgraded redoing); or we can look at how the redoings are occasioned, giving us a broad distinction between persistence and elaboration on the one hand (occasioned by the *lack* of a relevant response by B) versus interactive repair on the other hand (occasioned by a repair-initiating cue by B).

The point of a scheme like this is not primarily to classify but to make visible the larger possibility space. For instance, at position T−1, there may already be signs of trouble that may impact the unfolding of the sequence. Also, what kind of move is T−1: initiating or responding? The answer can determine how much 'out of the blue' it came and therefore how likely it was to result in a breakdown, with consequences for the kind of resolution needed [7]. Further, what happens at position T0 is to some degree graded. Some forms of interactive repair like the freeze-look [38] are formally quite similar to the absence of a relevant response, bringing into view a continuity that leads from persistence and elaboration to interactive repair.

Moving around this three-part sequential backbone also reveals other relevant dimensions. Some of these are related to the INTERACTION and its participants. Is the interaction agonistic or pro-social? What kind of activity do the participants (attempt to) engage in? How do the participants relate to each other in terms of kinship, dominance ranks or social bond? Others relate to the SEQUENCE [111,112]. Is it dyadic or multi-party? How are A and B engaged at position T−2: already in a focused encounter, minding their own business, engaging with others? Also, what happens after the first T+1: is the trouble resolved and the activity resumed or are more attempts at resolution needed?

Cross-cutting sequential aspects are matters of SEMIOTIC RESOURCES that can provide participants (and analysts) with food for inferences about communicative goals and intentional and attentional states. This includes the form of the behaviour (or lack of it) at T0: does it feature some repetition of T−1, as often happens in human interactive repair? Is it a response that indicates an adjacency pair mismatch (e.g. A initiates a carry request but B responds with social play)? Does it provide evidence of communicative trouble such as B trying to improve perceptual access [44]? Is there evidence for conventionalization or ritualization of a particular trouble display? It also includes multi-modal aspects of the communicative signals in relation to each other [113]: does the redoing at T+1 feature added multi-modal redundancy? What vocal, gestural, facial and postural resources are recruited? Also, it includes gaze as a proxy of attention: what is the gaze behaviour of A and B at T−1, at T0 (where trouble first surfaces), and at T+1 (putative resolution)?

By focusing on a bare-bones sequential structure along with observable behavioural patterns, the framework provides a coding scheme for the micro-analysis of redoings in the context of coordinated social behaviour (table 2). To demonstrate how this might be achieved, we present video examples on great ape social action coordination in our next section.

(a) Applying the species-agnostic coding framework

The next two video examples on great apes (along with two additional electronic supplementary material, Examples S2.1 and S2.2) showcase the coding framework and how it may be applied to study repair in non-human species.

The first example (electronic supplementary material, box 1, movie S1) involves multiple consecutive communicative attempts by a chimpanzee mother (self (A)) to initiate travel with her infant across a water pond (other (B)) (part of the dataset analysed in [88,114]). The infant is on the

Table 2. Simplified sequential coding scheme of three types of interactionally contingent redoings.

position	party	'persistence'	'elaboration'	'other-initiated repair'
T−2	B			
T−1	A (self)	A: [move]	A: [move]	A: [move]
T0	B (other)	B:	B:	B: [display of trouble]
T+1	A (self)	A: [move]	A: [MOVE]	A: [move]/[MOVE]
T+2	B			

right side of the water pond, while the mother is located on the left side of it. The mother's first signalling attempt involves a gesture (shake object, T−1, line 2). The infant does not seem to respond in a desired way ($T0_a = 10.2$ s, line 3, with the duration of T0 comprising the end of gesture production in A's previous turn until the beginning of A's gesture production in the next turn), thus the mother persists by repeating the initial gesture (shake object, $T{+}1_a$, line 4). This is again followed by a lack of desired response by the infant ($T0_b = 12.2$ s, line 5), after which the mother elaborates the signal (PRESENT BACK, $T{+}1_b$, line 6]. Finally, the infant jumps on the mother's back for joint travel, crossing the pond (T+2, line 7), which is treated as matching the desired goal, given than the mother stops pursuing a response.

A second example (electronic supplementary material, box 2, movie S2) involves a complex turn-taking sequence by two unrelated adult bonobo males, possibly evidencing interactive repair via repetition and elaboration with a contingent receiver response (taken from [18]). Diwani (self (A), higher-ranking) and Kelele (other (B), lower-ranking) are about to start a grooming activity. Kelele first approaches Diwani. They look at each other (T−2, line 1) until Diwani produces a first gesture towards Kelele (leg reach, T−1, line 2). Kelele seems to show no relevant response ($T0_a = 1.7$ s, line 3), upon which Diwani repeats the previous gesture (leg reach, $T{+}1_a$, line 4). Kelele still shows no (relevant) response ($T0_b = 2.2$ s, line 5), to which Diwani responds by using a new gesture (PRESENT ARM, $T{+}1_b$, line 6). The gesture is once more followed by a lack of relevant response by Kelele ($T0_c = 1.3$ s, line 7). Diwani persists by repeating the previous gesture (present arm, $T{+}1_c$, line 8). Kelele (after a 20 s pause) produces a gesture as a seemingly contingent response to Diwani's previous gesture (head jerk, $T0_d$, line 9), suggesting at least awareness of the other, and possibly of the initiating moves. Following Kelele's response, Diwani repeats his gesture once more (present arm, $T{+}1_d$, line 10), upon which Kelele starts to groom Diwani' arm, such that the grooming activity starts (T+2).

In contrast with the mother–infant carry examples (electronic supplementary material, box 1 and S2.1), the redoings in the grooming initiation examples (electronic supplementary material, box 2 and S2.2) involve particular communicative moves *by the receiver* in response to a grooming invitation (i.e. Kelele's head jerk gestures as seemingly contingent responses to Diwani's grooming invitation). These responses may or may not qualify as repair initiations or displays of trouble. What would it take to ascertain that these examples count as interactive repair? Here the attention of the framework to sequential aspects and semiotic resources comes to the fore. Using the minimal three-part sequential backbone, we could build a collection of cases of redoings (T+1) and see what kinds of behaviours (if any) recur in T0 positions to occasion them. If this yields evidence that some signals (e.g. head jerks) or behaviours (e.g. freeze responses) reliably occur as displays of trouble that occasion redoings (perhaps comparable to visible signals of trouble in human interaction displayed in the electronic supplementary material, Examples S3.1–S3.6), that might strengthen the case for it as a possible repair initiation, thus constituting evidence of interactive repair. Indeed, given that the head jerk reappears also in another interaction with the same dyad (electronic supplementary material, Example S2.2), there may be further occurrences of using such gesture types to initiate redoings in bonobos. Distributional evidence from collections of cases in their sequential context is key in making such determinations and in uncovering elements of the repair machinery across species.

6. Outlook

Across species, social interaction tends to be fast-paced, fluid, multi-modal and contingent. These features often lead to communicative breakdowns, providing us with the very phenomena we are interested in: repair strategies across species. However, they also make investigating these phenomena a challenge, as we have to deal with this fluidity and contingency when trying to determine the structure of sequences of communicative moves. There are no easy solutions and any approach will require an iterative combination of careful qualitative work, data-driven coding and systematic quantification. A general goal is to keep coding schemes as simple and straightforward as possible, providing objectivity and coding reliability as a top priority.

Although qualitative evidence as in the electronic supplementary material, boxes 1–2 and S2.1–S2.2 is important to demonstrate the phenomenon at hand, we note that a large array of data points from diverse species would be needed to provide a solid pool of data from which to draw more informed conclusions about the nature and structure of redoings and repair across species. Consequently, this paper does not aim at drawing any firm conclusions about the evolutionary origins of repair; instead our hope is that empirical studies will use this framework to produce comparative data, in order to address these and other questions in the future.

We have started here with data on non-human primates (particularly great apes), given their close genetic relationship to humans and the increasing availability of multi-modal recordings of social interaction. However, our framework is designedly species-agnostic and modality-agnostic, and can be extended to social communication across species, whether vocal duetting in birds [115], song exchanges in humpback

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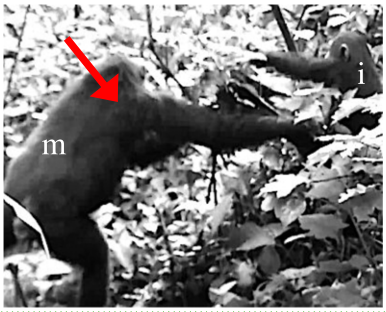
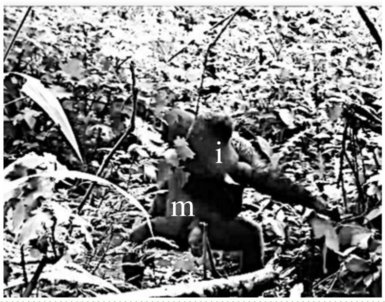
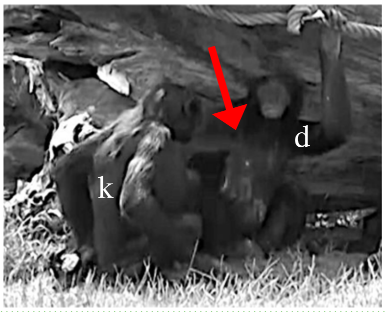
Box 1. Example 1 (movie s1). Possible cases of persistence and elaboration in a mother-infant carry initiation in chimpanzees. m= Mother, i = Infant. The red arrow points to relevant gestures. Video credit: Marlen Fröhlich and Simone Pika/Max Planck Institute for Ornithology (MPIO).

	position	party	move	video evidence (movie S1)
1	T-2	A and B	mutual gaze	
2	T-1	Self (A)	A: [shake object]	
3	$T0_a$	Other (B)	B: [lack of desired response, 10.2 sec]	
4	$T + 1_a$	Self (A)	A: [shake object]	
5	$T0_b$	Other (B)	B: [lack of desired response, 12.2 sec]	
6	$T + 1_b$	Self (A)	A: [PRESENT BACK]	
7	T + 2	A and B	start of joint travel	

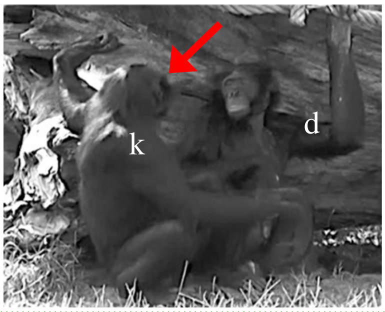
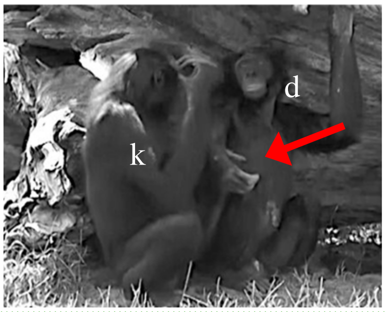
whales [116], referential signalling during cooperative hunting in coral reef fishes and moray eels [101], or any of a range of documented behaviours in ultra-social species and cooperative breeders or hunters. This calls for an interactional turn: to study the cognitive and behavioural underpinnings of flexible social communication, we need rich recordings that capture multi-modal interaction in its temporal and social contexts. Such materials allow for the sequential analysis of communicative

Box 2. Example 2 (movie s12). Possible case of persistence, elaboration and contingent receiver response in a turn-taking sequence of a grooming initiation in bonobos. d = Diwani, k = Kelele. The red arrow points to relevant gestures. Video credit: Raphaela Heesen and Emilie Genty/University of Neuchâtel.

	Position	party	move	video evidence (movie S2)
1	T-2	A and B	approach, mutual gaze	
2	T-1	Self (A)	A: [leg reach]	
3	$T0_a$	Other (B)	B: [lack of desired response, 1.7 sec]	
4	$T+1_a$	Self (A)	A: [leg reach]	
5	$T0_b$	Other (B)	B: [lack of desired response, 2.2 sec]	
6	$T+1_b$	Self (A)	A: [PRESENT ARM]	
7	$T0_c$	Other (B)	B: [lack of desired response, 1.3 sec]	
8	$T+1_c$	Self (A)	A: [present arm]	

(*Continued.*)

Box 2. (*Continued.*)

	Position	party	move	video evidence (movie S2)
9	TO_d	Other (B)	B: [head jerk]	
10	$T+1_d$	Self (A)	A: [present arm]	
11	$T+2$	A and B	start of grooming	

signals in context, broadening the scope from formal properties of individual signals and songs towards their sequential positioning, interactional contingency and communicative functions.

7. Conclusion

Joint action provides a unique empirical window to understand how individuals (human or non-human) co-construct a mutual state of togetherness. This mutual co-construction is particularly evident in cases of interactive repair, where the process of repair is distributed across recipient and producer. Here, we have shown that repair can have different forms, from self-initiated repair and its interactionally contingent forms like persistence and elaboration, to interactive repair—ultimately the most complex version of repair, thus far only evidenced in humans. These forms of repair rely on building blocks like self-monitoring, interactional contingency, flexibility in signalling and other-prompting. All of these building blocks combined can be considered the basic ingredients equipping a species for interactive repair. Given the public nature of redoings, the various versions of repair can be observed in non-human animal species and, when analysed in terms of the conceptual framework provided here, be used as yardsticks for the assessment of the evolutionary foundations of interactive repair.

The overall literature, including the examples presented here, seems to indicate that self-initiated repair is more common among non-human great apes, while other-initiated repair is more rare (if not absent). The cognitive and psychological requirements for interactive repair seem to go beyond turn-taking and intentionality, and notably include the ability to prompt others for self-repair, which ultimately may also require some form of perspective taking [117,118]. Moreover, other-initiated repair in humans seems to be ontogenetically scaffolded through conventionalized articulations of trouble sources via linguistic resources and hence may represent a uniquely human adaptation to minimize interactional trouble. Nonetheless, the multi-layered structure of repair supports the idea that some aspects of the behavioural and cognitive infrastructure of language may be phylogenetically quite ancient [52,64,119]. Evidence that some of repair's basic versions like signal repetition and modification are widespread in animal communication systems allows us to paint a picture of continuity and cumulativity in the evolution of robust communication.

Understanding the extent to which such interactive processes as repair are present in non-linguistic animals like non-human great apes also sheds light on the evolution of we-agency [24,120,121], and how this shapes language in modern humans [122]. In other words, comparative research of this kind is crucial in addressing the question of whether language is an adaptation for a fundamental problem of hyper-social species, namely the coordination of joint action [8].

Ethics. All data used in this article represents secondary data (i.e. no primary data has been collected). Ethical permission was received for all source articles from which data were drawn and can be found within the relevant articles cited in this paper.

Data accessibility. We use secondary data previously published in open access journals. Extra data are provided in the electronic supplementary material [123].

Authors' contributions. R.H.: conceptualization, formal analysis, investigation, methodology, resources, visualization, writing—original draft, writing—review and editing; M.F.: investigation, methodology, resources, writing—original draft, writing—review and editing; C.S.: conceptualization, methodology, writing—original draft, writing—review and editing; M.W.: validation, writing—review and editing; M.D.: conceptualization, formal analysis, investigation, methodology, resources, validation, visualization, writing—original draft, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

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