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Functional Information: a Graded Taxonomy of Difference Makers

Nir Fresco[1] · Simona Ginsburg[2] · Eva Jablonka[3]

Abstract There are many different notions of information in logic, epistemology, psychology, biology and cognitive science, which are employed differently in each discipline, often with little overlap. Since our interest here is in biological processes and organisms, we develop a taxonomy of functional information that extends the standard cue/signal distinction (in animal communication theory). Three general, main claims are advanced here. (1) This new taxonomy can be useful in describing learning and communication. (2) It avoids some problems that the natural/non-natural information distinction faces. (3) Functional information is produced through exploration and stabilisation processes.

1 Introduction

This paper provides a basis for a new concept of 'functional information' that can be used to explain cognition in an empirically informed manner. Our concept of 'functional information' is based on an intimate connection between learning and the intuitive notion of information. Receiving a piece of new information results, on average, in the *receiver* learning something new. 'Functional information' is understood as any difference in the (external or internal) environment of a system that has made a

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systematic, causal difference to the system's goal-directed behaviour. Thus understood, how much functional information a receiver can exploit in a given situation/context can change as a result of learning. As will become apparent throughout the paper, functional information is a special type of *causal* information, which in turn is a special type of *correlational* information.

We develop a taxonomy of functional information that extends the standard distinction—used in animal communication theory—between a 'cue' and a 'signal' (Section 2.1). On our view, a difference-maker (in a Batesonian sense) mediates between an object/feature/event or state of affairs and a receiver in a neo-Peircean fashion (Queiroz et al. 2008, 81). Accordingly, information is a triadic relation amongst a receiver, a difference-maker (e.g., a communicatory signal), and an object/feature/ event/state of affairs. From the receiver's perspective, a difference-maker is informational, because the receiver has evolved (phylogenetically or ontogenetically) to respond to this difference-maker in a regular and functional manner by altering its internal state. This taxonomy seeks to produce a coherent classification scheme with the aim of laying the groundwork for a concept that can be used in a variety of explanatory contexts.[1]

Various taxonomies of information already exist in the literature (e.g., Floridi 2011; Maynard Smith and Harper 2003; Millikan 2004; Queiroz et al. 2011; Scarantino and Piccinini 2010) with little agreement on how and when to use them. One may therefore wonder how the proposed taxonomy improves on the current situation. The short answer is that we build on a well-received taxonomy in animal communication theory (cue/signal) to clarify different *types* of so-called "non-natural" information that apply beyond nonhuman animal communication. It is often assumed that non-natural information and representation are extensionally equivalent. However, by understanding information from a functional perspective, we claim that there are instances of functional information that may qualify as "non-natural information", yet, calling them 'representations' lacks explanatory justification. Organisms exploit information about the environment (distal as well as proximal), and they may do so without necessarily representing the environmental feature(s) concerned.

Dretske was an influential philosopher who provided an account of natural information as a basis for understanding representation. On his view, if a system has the means of manipulating and exploiting the information it obtains, then the successful conversion of this information into a digital form constitutes the essence of cognitive activity (Dretske 1981, 142). According to Dretske, *natural information* is any event, condition, or state of affairs the occurrence of which is correlated with *s' being F* (where s is the source of information, and F is some property of s). Being F need not be a property of some object (e.g., the ball being blue), it can also stand for some occurring event (e.g., fire's burning). The informational content of a signal r (about *s being F*) is the conditional probability of *s' being F* given both r and k being 1 (where k is the receiver's epistemic state) (Dretske 1981, 65).

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[1] Possible applications include epistemology—differentiating between knowledge-that and knowledge-how on the basis of functional information (Najenson and Fresco in preparation), philosophy of computation—understanding computation as the processing of a subtype of functional information (Fresco and Wolf 2018), and cognitive science—understanding the limitations of using Shannon information as an explanatory notion in describing cognitive phenomena (Fresco in preparation). See also Mann (2018).

However, the conditions of information transmission, on Dretske's theory, are too strict. For they require lawful regularities between events (i.e., the conditional probability has to be 1). Scarantino's probabilistic difference maker theory (PDMT) of natural information improves on the Dretskean theory by relaxing this strict requirement.

On PDMT, natural information is a *triadic* relation amongst signals, state(s) of affairs, and background data. (Note the resemblance to our view of functional information as a triadic relation.) Carrying natural information about some state of affairs amounts to changing its probability relative to the background data (Scarantino 2015, 419). Background data are sets of propositions that are relevant when assessing instances of information. According to PDMT, information transmission does not occur in the absence of potential interpretative processes on the part of receivers. Scarantino stresses that "PDMT captures the theoretically central role that natural information plays in the explanatory efforts of cognitive scientists" (2015, 430).

However, both PDMT and Dretske's theory do not account for non-natural information. This is important since "the term 'information' in the sciences of mind both 'natural information' and […] 'non-natural information'" (ibid). Natural information is necessary, but arguably insufficient, for explaining cognition in informational terms.

The Taxonomy of Functional Information (ToFI) complements these two theories. Reliable correlations between a difference-maker and some state of affairs are necessary for explaining cognition in informational terms insofar as they support learning processes in receivers and (possibly) senders. These learning processes, we claim, are best explained by selectionist principles. 'Selection' is understood here in a broad, Pricean sense (Price 1995). Thus understood, it entails not only *Darwinian* selection, which includes replication and multiplication, but also *sample* selection that can contribute to adaptation via variation and selective retention without replication and multiplication. Elsewhere, we discuss these ideas in detail (Fresco et al. in preparation), and defend the claims that (a) the information a receiver can exploit, in the context of ontogenetic learning, increases with learning up to a bound, and (b) it is quantifiable (see Section 4.1).

We begin, in Section 2, by discussing the cue/signal and natural/non-natural information distinctions pertaining to biology, philosophy of mind, and the cognitive sciences. In Section 3, we explain the sense in which there is no functional information without interpretation. Our taxonomy is introduced and elaborated in Section 4. Section 5 offers a brief comparison of ToFI to two related conceptual frameworks of (functional) information: Skyrms' and Corning's. In Section 6, we briefly respond to two possible objections. The paper concludes in Section 7.

2 Related Notions of Information

Given that ToFI draws on existing, prevalent notions of information, it is helpful to introduce them as they are standardly used in the literature. We discuss two important distinctions: cue/signal, and natural/non-natural information.

2.1 Cue and Signal

Consider '*cue*' and '*signal*' in animal communication theory. Cue is defined as a "feature of the world, animate or inanimate, which can be used by an animal to guide future actions" (Maynard Smith and Harper 2003, 3; following Hasson 1994). Signal is defined as "any act or structure which alters the behavior of other organisms, which evolved because of that effect, and which is effective because the receiver's response has also evolved" (Maynard Smith and Harper 2003, 3).

What is the ontological status of cues and signals? A signal is an evolved act or structure in a *sender* that affects the evolved behaviour (or state) of another organism— a receiver—and which, on average, benefits both the sender and the receiver. Signals are associated with selection pressures on senders to convey information, and on receivers to respond to it. A cue, however, need not originate in another organism and may be informational to the evolved receiver without having been selected to alter the behaviour (or state) of receivers. A cue is a non-evolved feature that has accidentally provided the receiver with information, such as a rustle made by rodent alerting an owl to its presence.

Cues and signals can be classified as conveying correlational information. If an environmental or biological feature co-varies with some underlying quality that can be exploited by receivers, it qualifies as a cue. A cue is a regularity in the world that exclusively benefits the receiver (when there is no evolved sender). Receivers monitor cues insofar as the cues correlate with some conditions of interest (e.g., dark clouds correlate with rain, and a rustling sound in the leaves correlates with the movement of an animal—a potential prey). Like cues, signals—produced by some sender—correlate with the conditions of interest to the receiver (e.g., the waggle dance's duration correlates with the distance to the nectar source, and a signal's frequency may correlate with the size of some sender).

But even in animal communication theory 'information' is employed in at least four different ways (Stegmann 2013). (1) A signal s (e.g., the honeybee waggle dance) carrying information is a matter of correlation with some state of affairs S (the location of nectar): s carries information about S if s correlates with S. (2) A cue/signal s (e.g., dark clouds) carrying information is construed as a receiver-dependent feature, typically, as what receivers infer or predict (likely rain) when perceiving it. In short, it is sufficient for s to carry information about S when a receiver can infer S from s. (3) As a variation on the second construal, s carrying information is construed as also depending on the way in which the receiver processes it—typically if s evokes in the receiver a *representation* of the referent. Accordingly, s carries information about S only when it elicits in the receiver a representation of S. (4) A cue/signal carrying information is construed as referring to a receiver becoming more confident that a state obtains. Its informational value is directly measurable as the reduction of uncertainty. So, s carries information about S just when it carries positive mutual information with respect to S.

There is no generally accepted definition of information in animal communication theory, despite its central explanatory role. Information in the first sense above may be explained by probabilistic theories of natural information (e.g., PDMT): the structure of a honeybee dance raises the probability that nectar is 100 m to the left. The third construal makes representation conceptually or ontologically prior to information, whereas in cognitive science representation is often seen as a *type* of information.

The fourth construal equates information with the reduction of uncertainty, but the role of the receiver, though implicit, in that picture is unclear: mutual information (in Shannon's sense) is a receiver-independent measure.

ToFI adopts the second construal, giving the receiver a central role in the formation of information, whilst not making representation conceptually or ontologically prior to information. On our view, not every functional information is a representation (see Section 5). Some ants, for example, convey information about food and paths leading to it by leaving a pheromone trail on the ground. But "there is no need for the ant's nervous system to construct an internal representation of some rudimentary 'idea' of food […] you do not need a map if you are traveling by rail" (Johnson-Laird 1990, 3).

2.2 Natural and Non-natural Information

This brings us to another important, but problematic, distinction between natural and non-natural information in the spirit of the Gricean distinction between natural and non-natural meaning[2] (Grice 1957). Natural (or correlational) information depends on a correlation between a natural difference-maker and its correlate. In the Dretskean case, this correlation is a matter of natural law. But this requirement can be relaxed—as we have seen in PDMT—by simply requiring that natural information raise the probabilities of the state of affairs it is about. Smoke (as a cue) carries natural information about the presence of fire even in the absence of fire. It "is the type of correlation which natural selection can make use of" (Shea 2007, 420).

Non-natural, unlike natural, information need not directly correlate with what it is about. The linguistic statement 'There is smoke' carries non-natural information about smoke whether or not it correlates with the presence of smoke (Scarantino 2015, 430). On Grice's account, it is the speaker's intention that determines what is non-naturally meant by her utterance. The Gricean account is useful in making sense of linguistic communication. But linguistic constructs carry non-natural information by *convention*.

Why is the natural/non-natural information distinction problematic? Consider vervet alarm calls. These signals are correlated to a significant degree with the presence of a specific type of predator. They raise the probability of the corresponding predator being nearby, and are, thus, on PDMT, instances of *natural* information (Scarantino 2015, 431). However, they *functionally refer* to the presence of predators by virtue of contextual cues without necessarily being *strongly* correlated with their referents (Scarantino and Clay 2015). They correlate not only with the presence of a particular predator-type, but also, and possibly more strongly, with the fear of senders, their body posture as they attend to the specific predator, the escape movement of other vervets, and other states of affairs. As such, these signals carry non-natural information without being associated with the relevant classes of predators by convention. Generalising, a signal s carries non-natural information about a state of affairs S just when it has an effect on a receiver taking s to stand for S (Scarantino and Clay 2015, e3). There is neither conventionality nor intentionality involved in vervet alarm calls. This simply shows that the natural/non-natural information distinction is odd: what is *unnatural* about vervet alarm signals?

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[2] Natural meaning is factive and agent-independent (e.g., spots naturally mean measles). Non-natural meaning is non-factive and agent-dependent (e.g., those three rings on the bell non-naturally mean that the bus is full).

How can this tension be alleviated? According to PDMT, in producing a leopard alarm call, the signal raises the probability (*possibly* by only a small factor) of a leopard being present (so the call- to- leopard's- presence correlation *may* be weak overall). As such, the call carries natural information about leopards. But if, additionally, receivers responded to the call *as though* a leopard were present, then the call would also carry *non-natural* information about the presence of a leopard. That is, when the call depends not only on some relation between the sender and some state of affairs (e.g., the leopard's presence), but also on the way receivers respond to this type of call irrespective of the signal's actual referent, then it supposedly carries non-natural information about that referent.

However, this approach does not seem to solve the problem. First, why should functional reference be limited to signals? On Dretske's theory and PDMT, smoke carries natural information about fire. But if smoke as a *cue* has the functionally relevant, yet non-referential effect on a receiver, then it, too, carries non-natural information. Not only do *natural* signals (e.g., vervet alarm calls) carry *non-natural* information, but natural *cues* (e.g., smoke/fire, or dark clouds/rain), which are completely agent-independent, may also carry *non-natural* information. It is the appreciation of such correlations that evolves in receivers. And if there is more than one possible correlation available (as Scarantino and Clay persuasively argue), selection pressures could have resulted in an appreciation of a *different* correlation in receivers.

One may entertain several strategies for claiming that a cue carries either only *natural* information or *both* natural and non-natural information only under specific conditions. Non-natural information might depend, for example, on

(1) the type of cue, the type of (the responding) receiver, and the action that was phylogenetically or culturally selected for (in receivers of that type); or
(2) the type of cue, the type of receiver, and the action that it leads to in the receiver's ontogeny; or
(3) its being a cue (as a token) that is interpreted by a (particular) receiver that acts in some specific way.

So although smoke, for example, might carry non-natural information, there might be ways of arguing that its informational content is not of the same type of content conveyed by alarm calls (e.g., alarm calls elicit different escape behaviours that are specific to the *type* of predator). But that depends on the details of the relevant theory of non-natural information.

Second, non-natural information is often construed as being indistinguishable from representation. This is compatible with the third construal of cue/signal discussed above. But it seems to be a price too high to pay. Can there not be non-natural information that is not a *representation*? Again, much depends on the details of the relevant theory of non-natural information. A more straightforward distinction would be between natural information and representation, where it may be argued that the latter is somehow based on the former.

Third, convention may be construed as a result of some selection process, since many constraints should apply simultaneously for it to be robust. Convention typically arises through *cultural evolution*, and is most apparent in humans (especially through language). Non-conventional "natural" information is based on perceived regularities

that depend critically on *phylogenetic evolution* by natural selection of the receiver's sensory and neural apparatus. Understanding information functionally and focusing on the receiver's interpretation system—as we propose—recognises this fundamental commonality: both conventional/non-conventional information is the product of selection processes. Moreover, conventional information, can, under specified conditions, have both non-natural and natural facets (for a discussion see Millikan 2017).

3 No Functional Information without Interpretation

Before proposing our taxonomy in the next section, we elaborate on what we mean by 'function', 'functional information' and 'interpretation'. First, 'function' refers to the causal role of an act, event, structure, or process that has contributed to the systematically goal-directed behaviour of a system (see Jablonka 2002). Importantly, the level at which the causal role is described may vary for different systems and contexts, and this may determine the level to which goal-directedness may be attributed. For example, although most of the specific neural circuits that are activated during trial-and-error learning do not have a direct beneficial effect (since most lead to errors), learning through trial-and-error as a strategy is highly functional. Hence, although specific neural circuits play a causal role in learning, this is not the level at which natural selection has acted; rather it is the *strategy* that has been selected.

'Functional information' is understood as any difference in the external or internal environment of a system that has made a systematic, causal difference to the system's goal-directed behaviour. This is an extension of Bateson's definition of a 'bit of information' as "a difference which makes a difference" (1972, 315). His definition may indicate effectiveness in the sense of causation, but it may also be a normative indication of importance (Schroeder 2017). We opt for a causal/functional interpretation of difference-making. For a biological structure or process to have a systematic functional effect it must have been produced through phylogenetic and/or ontogenetic selection processes. But this is not enough for classifying something *qua* functional information. The difference between a contracted and a relaxed muscle fibre, for example, makes a systematic difference to an animal's goal-directed behaviour. Although the difference has functional consequences it is not an instance of functional *information*. One reason for that is that there must be a consistent relation between *variations in the spatiotemporal form* of the input and the corresponding changes in the receiver's response, because information is substrate neutral.

Functional information is the result of selection processes through phylogeny or ontogeny. Selection in its broadest sense is not limited to phylogeny (Campbell 1965). It also includes *ontogenetic* selection (e.g., being able to develop its song requires also that the young male bird gets a chance to hear the song sung by an adult bird early in life when the song can be learned, and the learning involves differential stabilisation processes as the bird practises) and *cultural* selection (e.g., the capacity for morality that develops robustly in living human beings following social and cultural pressures). In both cases selection includes exploration—sampling processes that can contribute to adaptation via variation and selective retention.

Trial-and-error learning is a good example of an exploration process that is followed by a selective stabilisation process. Navigation through a maze can proceed in many

different possible paths from the point of entry to the exit point. The initial space of possible paths is large. Any *failed* exploration of a particular path should, in principle, result in eliminating that particular one from the set of possible paths. Repeated exploration of this space leads to a selective stabilisation on a smaller subset of possible paths that *do* lead to the exit point. Selection in this sense implies that there are at least two options to select from.

Learning includes stabilisation processes (e.g., Caroni et al. 2012; Kelso 1997, Chapter 6; Striedter 2016, 87) typically through reinforcement, and in neural organisms there is usually neural exploration too. An adaptive outcome is reinforced when it changes the organism's behavioural dispositions. In trial-and-error learning both exploration and stabilisation processes occur at the behavioural *and* neural levels. However, there may be cases, such as in sensitisation and habituation (a form of non-associative learning that involves the modulation of reflexes), where no exploration process precedes the stabilisation process *during ontogeny*. Yet, this is so because the exploration process has already taken place *during phylogeny* through mutations and selection. Consequently, functional adaptations require lesser subsequent ontogenetic shaping.

Associative learning usually involves some level of ontogenetic exploration. In the case of instrumental conditioning, at the behavioural level, there has to be a means, through exploration, of producing responses that are adjustable. And there is, most likely, exploration at the neural level, too, with some population of synapses amongst those activated by the conjunction of an action and reinforcer becoming stabilised. In Pavlovian conditioning, responses to a conditioned stimulus that predict an unconditioned stimulus are likely to become selectively stabilised at the neural level, since it typically takes several trials to learn about the association (overt behavioural stabilisation of motor actions is also likely in most cases; see Kimmel (1965)).

Functional information requires that there be interpretation processes mediating inputs to the receiver and the corresponding outputs. 'Interpretation' refers to the processing of inputs to produce potentially adaptive responses. Crucially, the interpretation process is sensitive to variations in the input's spatiotemporal *organisation* or *form*, and it can lead to corresponding, systematic variations of the resulting response. Interpretation capacity is the result of natural selection, but it also develops during ontogeny in a context-sensitive manner (e.g., the receiver's environment acts as a physical constraint on exploration in that environment, and leads to adjustment of the interpretation processes). The difference between interpretive and non-interpretive processes can be explained by means of two examples.

Consider, first, the digestion of two pieces of steak that differ in their shape, size, thickness, and possibly in other physical characteristics. The digestion process will differ, of course, based on energetic constraints that have to do with breaking down the steaks by mechanical and chemical means. Any spatial and chemical connections amongst the steak molecules are broken until the resulting products can be either absorbed or discarded by the body. No organisation-sensitive interpretation process is needed, since variations in the input's organisation (e.g., whether the steak is star-shaped or rectangular) have no bearing on the outputs. The receiver's adaptive response is sensitive to the steaks' caloric and material content alone.

Contrast this with the processing of two audio stimuli of the same pitch, intensity, volume and duration. They consist of the same compressions (high-pressure regions)

and rarefactions (low-pressure regions), but are organised in a different order (e.g., one is 'high-high-low-low', and the other is 'low-high-high-low'). One stimulus may be a song (with certain phrase types and transition pattern complexity) to which a specific type of bird responds by changing its hormonal state. The other auditory stimulus, however, may be no more than noise for that bird. One stimulus has a functional significance for the receiver, whereas the other does not. Either way, both stimuli will undergo evaluative and interpretative processes in the receiver.

When two energetic/material inputs to the system are the *same* (e.g., two audio stimuli), but their spatiotemporal form (e.g., the low/high pattern) is *different*, then the variant form can lead to different results in the system. Variation in the sequence of phrases of a bird song (of an identical length and energetic signature) will, thus, be interpreted differently.

4 A Taxonomy of Functional Information (ToFI)

We are now in position to introduce our taxonomy of difference-makers through the definitions of four key notions:

- Datum
  - Sign
    - Signal
      - Symbol

Each of these notions is considered a difference-maker, rather than an information-*vehicle*—as it is often referred to in the literature. Being defined as a triadic relation, an information-vehicle cannot *convey* or *carry* functional information. The idea of information being carried stems from adopting a *realist*, *mind-independent* view of information as a commodity that can supposedly be carried/processed/etc. This view is criticised elsewhere (Fresco under review). Instead, a datum/sign/signal/symbol is a difference that makes a potential or actual difference to the receiver's reproductive success, to its chances of locating food (or other sources of energy), or to finding shelter, for example. Such difference makes the receiver respond to it in a way that it can (actually or potentially) alter the receiver's state in a (usually) functional manner.

But 'difference-making' plays a central role in the metaphysics of causation and that matter is unsettled. We remain neutral on the precise ontological nature of causation. Functional information, thus defined, entails "soft causation". Namely, it is not so much whether fire *is* the *cause* of (rather than being highly correlated with) smoke that is crucial for smoke being functionally informational to the receiver. Rather, on our view, smoke is a (potential or actual) cause for *the receiver acting* (or being disposed to act) in a particular manner in response. It is the reliable correlation between fire and smoke, rather than being a nomic regularity, that eventually (following phylogenetic or ontogenetic selection) gives rise to the receiver acting on it. Whether something newly encountered is a difference-maker can only be determined in a population of receivers and/or events not following a single event. (For a detailed analysis of potential and actual difference-makers in biology see Waters (2007)).

4.1 Data and Signs

Since ToFI is receiver-centric, an auxiliary definition of a 'receiver' is required before introducing and explicating the notions of 'datum' and 'sign'. (The notion of 'sender' is defined in Section 4.2 alongside that of 'signal'.)

Definition 1 – 'Receiver' A receiver is any evolved system that can accept, and interpret inputs.

Receivers can accept inputs from either an abiotic source (e.g., heat from a flame, sunlight, or dark clouds in the sky) or a biological sender (e.g., an insect, bee, or human). Receivers do not require evolved senders to exist in the world. Also, they need not be only complete organisms: different parts of the brain, for example, can be receivers under the relevant conditions. There is no restriction, too, on receivers being only biological entities: artificial computers, and their internal components can qualify as receivers in the context of *cultural* selection.

The basic building block of our taxonomy is a *datum*, and its immediate subtype is a *sign* (the more general counterpart of 'cue' on our taxonomy).

Definition 2 – 'Datum' A datum is a regular act, event, process or structure to which a receiver can, but does not yet, functionally respond by being sensitive to variations in its spatiotemporal form.

Definition 3 – 'Sign' A sign is a datum the receiver evolved to either overtly respond to or acquire an altered disposition to respond to through past phylogenetic, ontogenetic or cultural selection.[3,4]

The classification of something as a datum is relative to a *receiver* that can receive input from the environment, which is broadly understood to include also the internal milieu, not only what is *external* to the receiver. The specific datum does not require there having been evolution specifically for receiving and responding to it. The receiver has to be sensitive to the aforementioned Batesonian difference: information is a difference that *can* make a difference. Light waves reflecting from a potential prey cannot provide a blind star-nosed mole any optical information about nearby food. Light waves, thus, do not qualify as data for the star-nosed mole.

To make a *systematic, causal* difference to the receiver's goal-directed behaviour, the relevant feature of the world (e.g., smoke or dark clouds) has to exhibit some regularity. This regularity need not be nomological (as in Dretske's theory), but only highly probable (as in PDMT). It is *this regularity* that some would classify as natural information, since it is independent of learning. Learning allows the organism to exploit information from the difference-maker.

As already stressed, the receiver has to be sensitive to both variations in the *form*, rather than the particular physical makeup, and regularity of the input, because

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[3] The absence of something can be a sign, for example, when it is expected but missing.

[4] Note that this definition makes an implicit distinction between what may be called "descriptive" (the receiver's acquiring an *altered disposition* to respond) and "prescriptive" information (the receiver's action).

information is medium independent (Garson 2003, 927; Maynard Smith 2000, 179). A physical substance can be replaced with another and still give rise to the same functional information, if the spatiotemporal organisation remains unchanged. For example, the same functional information about the location of a particular object that is based on light waves reflecting from the object and its surroundings (through sight) can be based on the reflections of high frequency sound waves (through echolocation).

From an epistemological perspective, the classification of something as a datum that is *not* yet a sign (i.e., a non-sign datum) can typically be done only a-posteriori (relative to a receiver). By definition, a non-sign datum does not *yet* make a systematic, causal difference. When a difference-maker is classified as a sign due to a functional response it elicits in the receiver, it enables the classification of the very same difference-maker as a datum *at an earlier* phylogenetic or ontogenetic *time*. To qualify as a non-sign datum, the receiver should be able to detect the event, act, process or structure *d*, but not yet functionally respond to *d*. In that sense, being a datum is a necessary condition for being a sign (signs are a subtype of data). And being a non-sign datum is a causally necessary precondition for something being *informational* for a receiver: any difference-maker in ToFI is a subtype of a *datum*.

Here, the connection between ToFI and both natural information and a cue becomes apparent. A purely abiotic regularity, such as a reliable correlation between smoke and fire, or dark clouds and rain is a *datum* insofar as the receiver can detect the relevant physical properties, and *in principle* respond to their occurrence functionally. But a non-sign datum is a source of *potential* information. As such, a datum is (logically) a precursor to any environmental or biological feature qualifying as a cue. Crucially, it is the reliable correlation between the event/process/structure and its correlate that is the basis for the receiver's capacity for learning. The phylogenetic and/or ontogenetic processes that have shaped the interpretive systems of the receiver to respond to the difference-maker in a systematic and adaptive way determine the exploitable functional- informational content.

For a datum to qualify more narrowly as a sign, it should have made a systematic, causal difference to the receiver's goal-directed behaviour by eliciting, on average, an adaptive response.[5] It is in this sense that a *sign* differs from a *cue*. The latter can be accidental, whereas the former carries information in a *systematic* manner because of past selection. Every unconditioned stimulus or reinforcer (e.g., whatever elicits painful electric shock in mammals) is, therefore, a sign. An adaptive response should be broadly construed so as to include not only overt behavioural action, but also a change in a disposition to respond (e.g., predictions or beliefs about specific states of affairs). This goes back to the intimate relation between functional information and either phylogenetic or ontogenetic memory, for learning requires remembering.

A datum *becomes* a sign through a process of learning. A dark cloud *is* a sign for an ape that has learned that rain is likely to follow (the dark cloud is a conditioned stimulus). For not only does the ape see dark clouds, but it can also take appropriate action (e.g., seek shelter from the rain) on the basis of the predictive association between dark clouds and rain. By contrast, a dark cloud is a non-sign datum for a

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[5] In cases where a sender is involved in the information flow, there may be a conflict of interests between the sender and receiver (e.g., a "warning" pattern on the back of a nonpoisonous butterfly that elicits aversion in its predators). But phylogenetic selection implies some adaptive benefit, on average, to the sender, receiver or both.

baby ape, given its lack of functional importance for the ape at this stage of ontogenetic development. Later the ape actively constructs functional information from this natural correlation. Hence, Definition 3 provides the necessary and sufficient conditions for something to give rise to full-blown functional information. Given that a sign, unlike a *non-sign* datum, often enough elicits a *functional response* in the receiver, it yields non-zero functional information.

Consider a concrete example of ontogenetic selection during learning for clarifying the datum/sign distinction: a rat's learning process in a water maze experiment (Morris 1984). Placed in a small pool filled with water and fresh milk (to make the water murky), the rat starts swimming. Since it is averse to swimming, the rat tries to escape from the water. A small platform is submerged in the pool hidden just beneath the surface (see Fig. 1a). The rat recognises that the platform offers an escape from swimming when it first locates the platform. It undergoes various training trials in the pool, typically, having access to either distal or proximal environmental indicators that can be used to spatially navigate. (It can also learn about its own actions, but here we focus on learning from external indicators.) Spatial learning requires basic abilities, such as intact eyesight and swimming aptitude, as well as basic strategies, such as learning to climb on the platform and to swim away from the wall (Vorhees and Williams 2006).

The rat is exposed to many *data* in the environment in the sense that it receives multiple environmental stimuli (e.g., the smell of milk, or the sight of the pool's edges), yet not all of them result in a particular behavioural response. Some of these stimuli are not only received by the rat, but also trigger a positive functional response, because they become associated with a goal (e.g., finding an escape from swimming). Once the rat has learned about the platform in the pool, some data (e.g., a flag placed on top of the platform, or a beeping sound that the rat hears when approaching the platform) may turn out to be functionally significant for it. Other data, such as the smell of milk, either do not or cannot induce a similar effect. Such learning has made a systematic, causal difference to the rat's goal-directed, water-escape behaviour.

Thus, in the course of learning to navigate to the platform, the rat starts exploiting only some data as *signs*. Those data that are associated with a reward, i.e., locating the platform efficiently, become signs. A sign becomes more informational with the elimination of possible trajectories to that platform. Elsewhere, we develop a measure
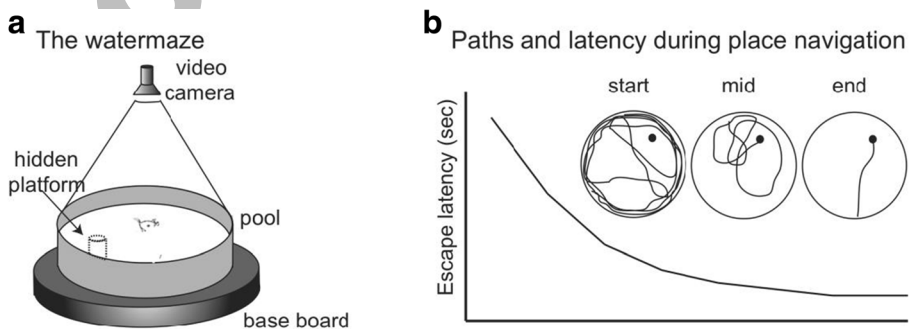

Fig. 1 **a** A water-maze set-up including a video-camera and a hidden platform. **b** Representative escape latency graph and swim paths across various stages of training: initial swimming at the side-walls, then circuitous paths across the pool, and finally directed path-navigation. (*Reproduced with permission* from Scholarpedia and Richard Morris)

of learned functional information based on a modified version of the Rescorla-Wagner learning rule, and show how informational increase over time can be modelled (Fresco et al. in preparation). The rat's learning process may be viewed as a selection process of eliminating possible trajectories through exploration until the rat selectively stablises on a minimal set of "optimal" trajectories (Fig. 1b graphically shows the decrease in the trajectories explored).

Through learning, the quantity of functional information a receiver can exploit by observing a difference-maker (a sign in this example) depends on how the receiver interprets the difference-maker. The interpretation process depends on the receiver's learning history, thereby suggesting that the receiver can interpret difference-makers in different ways at different times. What others have called natural information (e.g., the correlation between the flag and platform's location) is part of what makes it possible for a receiver to learn. However, the rat initially does not associate the flag (as a datum) with the platform (the means to achieving a goal—an escape from swimming). Once it does so, further learning increases the amount of functional information it can exploit, until it stabilises on "optimal" trajectories to the platform without further improvement. (Trajectories are *optimal* only in the sense of being the shortest ones taken in late stages of the experiment.)

4.2 Signals and Symbols

Having distinguished signs from non-sign data, we introduce the auxiliary notion of a 'sender' and the next ingredient in our taxonomy: a *signal*.

Definition 4 – 'Sender' A sender is any evolved system that can systematically produce, encode, and transmit signs to a receiver.

Definition 5 – 'Signal' A signal is a sign that may have a learned component and is sent by a sender that evolved, through past natural, ontogenetic or cultural selection, to emit it as a sign for particular receiver types.

A 'sender' is the counterpart of a 'receiver', and together they form a signalling system (Lewis 1969; Skyrms 2010). In sender–receiver signalling games, the sender observes some state of the world and selects a signal to send from a set of possible signals. The receiver observes that signal and acts accordingly. What matters here is that senders coevolve with receivers through phylogeny, ontogeny, or culture, though their interests are not necessarily perfectly aligned. What the sender does can help the receiver to perform functions that loop back, making both of them more likely to survive, reproduce or preserve their current settings (Millikan 2009, 397).[6] (Such coordination is not a precondition for *receivers* to exist.) It is advantageous to be a sender when the reward from signalling exceeds the cost of signalling. It is advantageous to be a signal-receiver when acting on the signal brings benefits above ignoring it (Cao 2012, 51).

A signal is a functionally referential sign that is transmitted by a sender, and that evolved in the sender to enable functional information to be exploited by the receiver.

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[6] This suggests that abiotic "senders" (e.g., black clouds, or smoke) are senders only *metaphorically*.

Whereas a sign, strictly, only implies an informed *receiver*, a signal implies (in addition) a *sender* that evolved to emit it, and is engaged in the flow of information. That is, whilst a sign may be environmental (in a broad sense), a signal originates in a sender that was selected to emit signs for receivers. A signal systematically co-varies with the presence or absence of a particular state of affairs. Definition 5 is compatible with inter-organism communication, but it does not preclude intra-organism communication. Nevertheless, spelling out sender-receiver configurations at a sub-organismal level is a challenging task not undertaken here (see Cao (2012)).

Importantly, signals, unlike non-signal signs, often come at a cost. Senders invest in producing reliable signals, and receivers, who benefit from responding to reliable signals, exert pressure on senders to invest in the reliability of the signal by responding favourably to reliable signals whilst ignoring unreliable ones (Zahavi 2008).

A concrete example of animal communication is useful to further clarify the notion of a 'signal': vervet alarm calls. Vervets produce acoustically different alarm calls to leopards, eagles, and snakes, where each type of call elicits a different, adaptive response. Individuals run into trees when they hear a leopard alarm, look up in the air when they hear an eagle alarm, and stand up on their hind legs and peer into the grass around them when they hear a snake alarm call (Cheney and Seyfarth 1990). These predator-specific behaviours evolved, since they were, on average, beneficial whenever the corresponding predator approached in the past.

How do the signals produced by vervet monkeys fit in with the idea of exploration/stabilisation? Unlike adults, infants and juveniles make many mistakes giving alarm calls to species that pose no danger to them. Sometimes, a particular alarm call may be produced in the absence of its corresponding referent (e.g., an eagle). The mistakes infants make are, however, not random. "Vervet infants behave as if they are predisposed from birth to divide other species into broadly different classes: predator versus non-predator and, within the former class, terrestrial carnivores, eagles, and snakes" (Seyfarth and Cheney 2010, 94). Despite the phylogenetic ("innate") basis for the production and usage of these calls, there is much fine-tuning (exploration) through ontogenetic and social learning in the response to these calls. The decrease in the emission of irrelevant calls is a function of learning, and the amount of functional information in the signals increases with time and learning trials.

Definition 5 is compatible with the usage of 'signal' in animal communication theory, but it improves on and generalises the standard definition: the 'evolvability' aspect can be strategic-general, rather than a specifically evolved, communicative predisposition, and selection need not be *only* phylogenetic. A signal, as in some cases of animal communication (and in human language), can evolve through cultural evolution and require ontogenetic learning for its acquisition and use. According to ToFI, a signal is a special type of a sign.

Consider a toy example involving two non-conspecific animals: *Birdy* and *Aposemy*. The former is a bird that typically feeds on butterflies in its natural habitat. The latter is a poisonous butterfly that lives in a different, *darker* environment. When Birdy finds itself outside its natural environment, it adapts to preying on local insects. Suppose that it tries to prey on Aposemy, whose handling proves difficult. Suppose further that during its struggle when Birdy slightly pecks Aposemy and is disgusted by the results, Aposemy accidentally opens its wings, thereby fully revealing their red and yellow polka-dot pattern. Following that act coupled with the nasty taste of Aposemy, Birdy

lets Aposemy go. The specific pattern, which Birdy has not seen before and would not have otherwise avoided (though Birdy is slightly predisposed to avoid red-and-yellow patterns), has now become associated with the nasty taste for Birdy. Spreading the wings has now become associated with safety for Aposemy. In future encounters, Aposemy immediately opens its wings to warn off Birdy, and the latter retracts. Aposemy's polka-dot pattern is an example of a signal that has evolved through *ontogeny* for its use by Birdy and Aposemy.[7]

Another important difference of ToFI's 'signal' from its animal communication counterpart is what constitutes the *content* of a signal. Stegmann (2006) proposes two ways of extending the standard definition so as to specify the signal's content. On one proposal, a signal has a causal, evolutionarily designed effect in development that is mediated through the evolved response of a receiver. The content of a signal is equated with an evolutionarily designed effect in the receiver. The content of a leopard alarm call, for example, is *Climb up the nearest tree!* since it is evolutionarily designed to elicit in the receiver a particular behaviour to avoid the predator. This is a problematic proposal, because ethologists typically take signals to refer to either a property of the sender or a third party, but not to how the receiver should respond (Stegmann 2006, 1019). Besides, whilst the calls evolved to communicate different types of danger to conspecifics, the monkeys seem not to have a psychological *intention* to warn others (Cheney and Seyfarth 1990; Seyfarth and Cheney 2010).

On another proposal, inspired by consumer-based teleosemantic theories of content (e.g., Millikan 2009; Papineau 2003), a signal's content is equated with the *circumstance* responsible for the evolution of the receiver's behavioural response. If that circumstance concerns a third party (an eagle), then the third party is the signal's content (*an eagle is approaching*). If that circumstance concerns a property of the sender, then that property is the signal's content (the roar of a male red deer signals that it is in good shape for a fight). However, this proposal faces the problem of indeterminacy of content. An alarm call correlates not only with the presence of a particular predator-type, but also with the fear of the signaller and its body posture, and possibly other circumstances.

According to ToFI, the content of a signal is determined not only by the presence (or absence) of some circumstance, but also with the evolved receiver's response. The content of a leopard alarm call is uniquely determined by the presence of the leopard *and* the escape behaviour of the other vervets. The same idea applies to signs as well. The content of a sign is determined by a reliable, natural regularity,[8] but also the receiver's adaptive response to it. Dark clouds do not refer to the likely rain for a baby ape, yet they do for a mature ape that has learned to associate dark clouds with the likely occurrence of rain. Further work is required to fully account for the content of signs and signals.

To complete our taxonomy we define the notion of 'symbol' (cf. Deacon 1997; Jablonka and Lamb 2014, 196).

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[7] Mann similarly argues that sometimes signs (which he calls cues) become signals when the receiver's behaviour turns out to benefit the sender—through a process of ritualisation Mann (2018).

[8] See Barwise and Seligman (1994) for an analysis of natural regularity.

Definition 6 – 'Symbol' A symbol is an intentional signal that is part of a systematic, rule-governed, self-referential-signalling system.

The discussion of symbolic, functional information here is brief. Its aim is to give only an overall picture of how the progression from a datum to symbol tracks the degree to which functional information is the result of different types of selection processes. Symbolic systems, in general, have emerged as a result of gene-culture co-evolution, where cumulative social processes involved some form of selective retention of cultural variants that enabled the elaboration, and growing complexity of the cultural practices (Jablonka and Lamb 2014, 223). Signals become symbols when (i) they are intentional (i.e., exhibit an *aboutness* relation), (ii) they are part of a rule-governed, cultural system, and (iii) their contents depend on their relations to objects and events in the world or to other signals in the system. The paradigmatic example for a rule-governed system of intentional signals is natural language. Young children are able to learn and apply language-specific rules prior to any formal tuition of the local rules of grammar by simply being embedded in the relevant social contexts.

Symbolic systems allow reference to things that do not even exist. It is here that the correlation requirement discussed above in relation to a datum is relaxed (see also Section 6). In special cases, such as logic and mathematics, symbols may even refer *only* to other symbols without losing their content. Some instances of symbolic, functional information, such as tautologies and contradictions, behave differently than *contingent*, functional information (that is based, for example, on dark clouds or a bird's song). This is the result of applying logical operations to propositions that render their reference to reality either trivial (tautologies) or impossible (contradictions).

When signals are part of a rule-governed, self-referential system, they acquire what is typically called *semantic content* through the *aboutness* relation to their referents. Propositions and statements can be either true or false due to the relations they bear to states of affairs. A vervet may mistake a bobcat for a leopard under some conditions, but there is no *falsity* involved in that scenario. It is a case of misidentification: the alarm call will result in the same escape behaviour in other vervets and the signaller's fear will be just the same. The contrast to mistake is *functional accuracy* rather than *truth*. An organism either accurately perceives objects and events in the environment or mistakenly perceives them as something else. Symbols can be organised in nested hierarchical structures (e.g., words nested in phrases, which are nested in sentences), and their semantic content and veracity depend on their larger symbolic context. The proposition 'There is a leopard 5 metres away' will be true when a leopard *is* five metres away, and false otherwise. With few exceptions, truth conditions can be assigned to symbolic messages, not to non-symbolic signals.

If ToFI holds up across different domains of cognition, then it provides an opportunity to investigate how symbolic systems have evolved from more basic forms of functional information in the animal kingdom. This is despite the fact that symbolic, functional information does not seem to exist in nonhuman animal communication, because nonhuman animal signals do not form a self-referential system of intentional signals (Jablonka and Lamb 2014, 201). Symbolic systems, predominantly language, may be viewed functionally as the systematic instruction of imagination—enabling one to *imagine* the intended, communicated experience, rather than directly experiencing it (Dor 2014).

5 A Brief Comparison with Previous Works

Since the usage of functional-informational terms in the literature is variable, we briefly compare ToFI to two related conceptual frameworks: Skyrms's signalling game theory, and Corning's control information. Skyrms' theory (like ToFI) builds on animal communication theory, but provides a framework for quantifying information in signals using the replicator dynamics model of evolution. It deals with the natural emergence of signalling systems, including signs with content that emerge from phylogenetic and ontogenetic evolution. However, some natural signs, such as smoke, contain, on Skyrms' view, information about states that is "out there" in the world (an idea that we deny). What receivers need to learn is how to utilise that information (Skyrms 2010, 39). A signal is a function of one or more variables that carries information with respect to a world state in a *sender-receiver system*. Its informational content consists in how the signal changes probabilities of world states.

There are important similarities and differences between Skyrms' theory and ToFI. According to Skyrms, "[i]nformation *about acts* arrives on the scene when we learn to react appropriately to the information about states contained in the smoke" (2010, 40, italics original). Insofar as it is evolution or learning that leads to the formation of information in a signalling system,[9] ToFI resembles Skyrms' theory. He claims that signals have no pre-assigned content; their content is acquired through the interaction of the strategies of senders and receivers (Skyrms 2010, 35). Likewise, according to ToFI, functional information is produced through (phylogenetic, ontogenetic or cultural) selection processes: it does not exist in the absence of receivers. However, Skyrms' theory focuses mostly on measuring the contents of signals in systems *at equilibrium*. ToFI, by contrast, focuses on the *dynamics* of the change occurring in (successful) learning processes where a learner may eventually reach an asymptote at which point she can exploit maximum functional information in the relevant context through some difference-maker (e.g., a sign).

Next, consider Corning's view, according to which functional information is cybernetic and critically involves a receiver. "Living systems and human organizations are largely shaped by 'instructions' (functional information) and by cybernetic control processes" (Corning 2012, 305). Functional information cannot do anything without the presence of a receiver using it to do purposeful work (Corning 2007, 301). 'Control information' is the capacity to control the acquisition, disposition and utilisation of matter/energy in purposive processes. It is a relationship between a particular cybernetic system and its external and internal environment.[10] Information is neither an entity nor a mechanism, but rather a relational property (as in ToFI). The environment contains latent information, which is actualised when a purposeful receiver uses it.

Corning's 'latent information' resembles our 'datum' insofar as something's being a datum is a necessary, but insufficient, condition for a sign to be informational to a receiver. The information potential in a datum manifests itself through natural,

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[9] This disclaimer is important, because Skyrms also writes that "*[t]he world is full of information. It is not the sole province of biological systems*" (2010, 44, italics original).

[10] Sloman similarly argues that control information is probably what evolved first in biological organisms, such as bacteria (2011, 404).

ontogenetic or cultural selection processes, and, specifically, in the case of an individual receiver through learning. However, unlike Corning's theory, ToFI distinguishes—at the level of a sign—between an overt response and the acquisition of an altered disposition to respond (recall Definition 3 above). An altered disposition to respond may not be straightforward to operationalise by measuring the quantity of thermodynamic work that is performed in a cybernetic process as Corning proposes.

6 Replies to Objections

Before concluding, we reply to two possible objections to our analysis. The first objection is that *functional information* is supposedly equivalent to *representation*. We have already hinted at such a possible objection. Indeed, the rat in the maze uses a cognitive map representing its routes to the submerged platform using the informative flag. Our analysis, on this objection, does not contribute to understanding *information* as such in theorising about cognition.

A complete response exceeds the scope of this paper. However, we note that a representation is a "model" of the world (or organism-world relations), and not every instance of functional information includes such a modelling relation. Anaerobic marine bacteria in the northern hemisphere orient themselves away from toxic, oxygen-rich surface water by way of tiny inner magnets. Their orientation towards geomagnetic north directs the bacteria into deeper, relatively oxygen-poor water. However, the bacteria's movements are more reliably correlated with magnetic fields than with oxygen-poor water (Millikan 2009, 406). Information about the magnetic north is undoubtedly functionally useful for these bacteria (contributing to their survival over evolutionary time). However, *pace* Millikan, why should we assume that the bacteria *model* the relevant pattern of relation between the magnetic north and oxygen-poor water environments? Describing this behaviour in representational, rather than informational, terms is not explanatorily useful. (A similar argument is made by Burge (2010, 299–300).) We do not contest the fact that many instances of *functional information* also qualify as *representations*, only that the former and latter are equivalent.

A second objection is that we have supposedly no justification for calling what we analyse *information* proper, since we have not shown how functional information relates to Shannon information (as Dretske did with his notion of semantic information).

Our response is that functional information requires there to be a correlation—just as Shannon requires—between two variables. This correlation, as argued above, is a necessary, not sufficient, condition for non-symbolic information to be *functional*. Shannon information is insufficient for elucidating the causal relations amongst sensory inputs and action-selection relative to the organism's goals. These relations depend on the organism's evolved capacity to modify relevant aspects of its internal state as a function of changes in the environment. Accordingly, functional information also requires that (1) the correlation be causal (in the "soft" sense described above), and (2) valence be attributed to the *causal* correlation (fitness in the phylogenetic case and reduction in uncertainty in the learning, ontogenetic case).

7 Conclusion

We have proposed a graded taxonomy of functional information. Accordingly, a datum is a regular feature of the world that a receiver is *capable of* functionally responding to. It is the basis for all other difference-makers. A sign is a special type of datum that the receiver overtly *responds* to or *acquires an altered disposition* to respond to. A signal is a special type of a (communicatory) sign that *requires a sender* that evolved to emit it. This clearly distinguishes signs from signals, but also explains how signs can "upgrade" to signals under the right conditions. Finally, a symbol is a unique type of signal that is part of a systematic, *rule-governed self-referential* system. It is the basis of language—the hallmark of the human species. Much further work is required to fully develop this notion and its relation to its signal ancestor.

Functional information changes as the receiver learns. We have claimed that it is produced and modified through exploration and stabilisation processes. When a datum upgrades to a sign through a learning process, the receiver's interpretation system undergoes a stabilisation process in response to the environmental condition. A rat can learn to find a hidden platform by exploiting spatial information from a correlated, visual sign depending on its own prior experience. It can improve in such a task as it stabilises on smaller sets of trajectories leading to the platform. A vervet learns to emit and respond to others' alarm calls more accurately and with more certainty with experience. Young children can learn their native language prior to any formal tuition of the local rules of grammar by being embedded in the relevant social contexts.

This taxonomy clarifies different aspects of learning and communication, and avoids using the problematic notion of non-natural information. It provides the conceptual background allowing a further analysis of the selectionist principles underlying different types of learning and their relation to the formation and updating of functional information.

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