Article

Information in Explaining Cognition: How to Evaluate It?

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Abstract: The claims that “The brain processes information” or “Cognition is information processing” are accepted as truisms in cognitive science. However, it is unclear how to evaluate such claims absent a specification of “information” as it is used by neurocognitive theories. The aim of this article is, thus, to identify the key features of information that information-based neurocognitive theories posit. A systematic identification of these features can reveal the explanatory role that information plays in specific neurocognitive theories, and can, therefore, be both theoretically and practically important. These features can be used, in turn, as desiderata against which candidate theories of information may be evaluated. After discussing some characteristics of explanation in cognitive science and their implications for “information”, three notions are briefly introduced: natural, sensory, and endogenous information. Subsequently, six desiderata are identified and defended based on cognitive scientific practices. The global workspace theory of consciousness is then used as a specific case study that arguably posits either five or six corresponding features of information.

Keywords: cognition; cognitive science; sender; receiver; natural information; endogenous information; sensory information; desiderata; semantic information; scientific explanation

1. Introduction

How is “information” used in the cognitive sciences? There is broad agreement that the brain and cognition involve information processing, and many theories explain neural, cognitive, and behavioural phenomena in informational terms [1–4]. However, given that “information” means different things to different people, it is hard to answer this question.

The need to bring conceptual order to the messy domain of existing theories of information was already recognised by Dretske [5]. There are many competing theories, ranging from quantitative theories of information flow [6–8], through evolutionary signalling game theories [9,10], to theories of semantic and biosemantic information [5,11–14]. In order to evaluate which theory of information should be appealed to in cognitive scientific explanations, one should first determine which notion of information is invoked.

The present analysis is motivated by the explanatory work semantic information often does in the cognitive sciences in virtue of its semantic properties. Such information can be found, for example, in animal communication studies. Referential signals exchanged between animals, plus possibly specific features of the sender, allow them to infer environmental states. Paradigmatic cases include the honeybee waggle dance and vervet alarm calls. What enables animals to make predictions based on such signals are correlations between signals and worldly states or events. The waggle dance correlates with the distance to and direction of nectar-rich flowers. Vervets produce acoustically distinct calls in response to (three) different predator types. The semantic content of these signals is supposedly the state or event with which the signal correlates [15].

More generally, semantic information in cognitive explanations often tracks the way changes occurring in the receiver’s environment correlate with changes in the receiver. Cognitive explanations typically aim to understand how purposeful behaviour is produced by representations of the environment. Such representations supposedly carry different
types of semantic information. Motor representations carry prescriptive information to behave in a specific way, whereas perceptual representations carry descriptive information about environmental states [16]. Semantic information is believed to close the loop between the signal and the environment: the signal is shaped by the environmental state, and the receiver’s actions are (eventually) directed toward some environmental state [17].

Insofar as “information” is a theoretical construct that binds together different cognitive systems studied across the cognitive sciences, this concept—even when various subtypes of information are concerned—should be explicated. For it is often unclear which notion of information is used, and whether this notion does explanatory work in a respective neurocognitive theory or model. The scientist would, thus, do well to be explicit about the notion of information that is used, if “information” is to play an explanatory role in their neurocognitive theory. The desiderata below can be used to match neurocognitive theories to suitable theories of information.

A key assumption underlying the motivation for specifying the desiderata is that information does explanatory work in the neurocognitive theory \( T \) and is not merely an explanatory gloss. Whether or not information does explanatory work is determined by \( T \), rather than by the candidate information theory. If information plays an explanatory role in \( T \), then the scientist should heed the proposed desiderata. In this sense, information should satisfy an analogue of Ramsey’s “job description” challenge for representational explanations [18] (p. 34) by answering two questions affirmatively with respect to \( T \). (a) Is there an explanatory benefit in \( T \) describing some cognitive, neural, or biological processes in informational terms? (b) If \( T \) uses “information” in describing such processes, do the underlying cognitive/neural/biological states play this sort of informational role, and, if so, how? The ensuing analysis provides a means for evaluating whether a candidate information theory entails the informational features that are posited in \( T \).

The aim of the article is, thus, to identify the key features of information that a candidate theory of information should explain to qualify as a potentially good match for the neurocognitive theory \( T \), which posits these informational features. The corresponding theory of information should satisfy the desiderata (rather than \( T \) as a neurocognitive theory). Given that some neurocognitive theories may posit very few features, and other will posit more, the proposed desiderata are not intended as necessary conditions. Moreover, the desiderata are defeasible and may change alongside the evolution of successful practices of the cognitive sciences, for they depend on what the requirements of \( T \) are with respect to \( T \)'s predictive accuracy, fruitfulness, and biological plausibility, for example.

We begin (Section 2) by briefly discussing some characteristics of explanation in the cognitive sciences in order to better motivate the proposed desiderata. In Section 3, a conceptual trichotomy of information is proposed as a backdrop for identifying and defending general desiderata for a cognition-friendly theory of information (in Section 4). In Section 5, we briefly evaluate the global workspace theory of consciousness—as a case study—for its appeal to different features of information. Section 6 concludes the article.

2. Unificatory Explanation in the Cognitive Sciences?

The success of the present analysis leans heavily on what qualifies as the “explanatory power” of a given neurocognitive theory, and the “explanatory role” of “information” in that theory. There are many theories of explanation out there with different implications for what is and is not explanatory, under which conditions, and why. For now, we briefly discuss some features of explanation in the cognitive sciences and their implications for the concept of information.

As an interdisciplinary endeavour, the cognitive sciences should supposedly be unified under some general standards of explanation, but current scientific practices may suggest otherwise. It is unclear whether the multiple research programmes ultimately converge together or are only loosely coordinated. The latter alternative leads to some form of explanatory pluralism in which explanations are simply mutually constrained [19]. There exist many cognitive phenomena, often calling for competing explanations, and some
approaches and models of these phenomena will likely be more explanatorily useful than others [20]. The upshot is that if multiple information-processing research programmes should be unified, or even only merely coordinated, in virtue of some common concept of “information”, then “information” should be consistent across these programmes, thereby placing a greater clarificatory burden on the scientists.

The explanatory power of “information” as a theoretical concept cannot be determined independently of a theory. Does “information” contribute to the neurocognitive theory’s predictive accuracy? (How well can the theory explain the available data by appealing to “information”?) Does it contribute to the theory’s fruitfulness? (How well can the theory predict “novel” facts and deal with anomalies by appealing to “information”?) Does it contribute to the theory’s logical consistency? (Are the various appeals to “information” in the theory consistent?) [21] (pp. 53–54). As theories develop, new explanations are offered and tested. In that process, concepts, such as “computation”, “information”, and “representation”, are refined. Consequently, the desiderata are not intended to be fixed and will likely change alongside the evolution of successful explanatory practices in the cognitive sciences.

Whether the cognitive sciences are (or should be) unified or simply coordinated, the desiderata can be useful. If neurocognitive theories trade in “information” and “information processing” in describing the entities and processes concerned, then regimenting usage by identifying key features of “information” can contribute to the unificatory effort. Nevertheless, even if cognitive scientists adopt divide-and-conquer strategies, thereby leading to explanatory pluralism, the desiderata can help to chart some mutual constraints on the various theories indicating where coordination is possible and where it is not. Regimenting the usage of “information” can contribute to stressing the explanatory role that this concept plays in information-based neurocognitive theories.

3. A Useful Trichotomy of Information in the Cognitive Sciences

As a backdrop for identifying and defending the desiderata, in this section we propose a trichotomy of information that distinguishes between some very general uses of “information” in the cognitive sciences. One notion refers to the correlation between different worldly events or states that can be exploited by the receiving organism in guiding its actions. Another notion refers to the content of sensory, motor, and cognitive states of an organism. We first briefly discuss a common conceptual distinction in the philosophy of science that is intended to encompass these two notions: natural and non-natural information. We then introduce the proposed trichotomy.

3.1. Natural and Non-Natural Information: The Gricean Path

The distinction between natural and non-natural information follows its Gricean counterpart between natural and non-natural meaning [22]. Natural meaning is both factive and agent-independent (e.g., these spots naturally mean measles). Non-natural meaning is non-factive and agent-dependent (e.g., three rings on the bell non-naturally mean that the bus is full—even when the bus is not full). In recent years, the Gricean analysis has been taken as distinguishing between two different types of information-carrying vehicle. Let us describe how the Gricean distinction is applied to information.

Natural (or correlational) information depends on a correlation between a bearer of natural information and its correlate. For Dretske, this correlation is both factive and agent-independent (e.g., these spots naturally mean measles). Non-natural meaning is non-factive and agent-dependent (e.g., three rings on the bell non-naturally mean that the bus is full—even when the bus is not full). In recent years, the Gricean analysis has been taken as distinguishing between two different types of information-carrying vehicle. Let us describe how the Gricean distinction is applied to information.

Natural (or correlational) information depends on a correlation between a bearer of natural information and its correlate. For Dretske, this correlation is both factive (i.e., the conditional probability that s is in state F, given that the cue—or signal—r is equal to 1) and lawful (this conditional probability relation is fixed by a law of nature, rather than by mere coincidences). However, these requirements are, arguably, too strong, and should be relaxed (as proposed, e.g., by Scarantino [14]) such that natural information simply increases the probability of the state of affairs it is about. (Still, only reliable correlations qualify as natural information.) As such, the content of natural information is not a fact, but the extent to which a given possibility is more or less likely. Hence, smoke carries
natural information about the presence of fire—even in the absence of fire. Similarly, insofar as hormone-mediated maternal effects can adaptively modulate offspring developmental trajectories in variable, yet predictable, environments [23], prenatal hormone levels carry natural information about the environmental state due to parental responses to that very environment. Gricean natural meaning roughly corresponds to a cue or signal.

Non-natural information, however, need not reliably correlate with what it is about, and can be false. The statement “There is smoke” carries non-natural information about smoke whether it correlates with the presence of smoke or not [14] (p. 430). A visual representation of an external object with a 3D shape, S, likewise carries non-natural information about S’ spatial features that allows a mental rotation of this representation when S and another shape call for a comparison [24]. Such representations may, of course, be erroneous. One may misperceive a surface-colour gradient—due to errors in normal sensory processing—as an illumination gradient. A schizophrenic, or someone under the influence of psychedelic drugs, may see, hear, or smell things that do not exist outside their mind, thereby misrepresenting reality. Unlike natural information, non-natural information—just like non-natural meaning—is often understood as representation [14] (p. 430), Refs. [25,26] that is alethically evaluable.

Nonetheless, it is not clear whether non-natural information and representation are extensionally equivalent [13,27]. For one thing, even though some may be “convinced that a naturalistic theory of non-natural information/representation ought to be grounded in natural information” [14] (p. 430), it is unclear how that may be so for resemblance-based representation (recall the mental rotation task above). The answer to the above question also depends on whether one adopts a more restrictive or liberal concept of representation. On a liberal concept, such as Millikan’s [28], representation simply requires that a consumer subsystem can fulfil its task normally when the producer subsystem goes into a state (e.g., eye blinking—as a defensive reflex action that protects the corneal surface from potential physical injury) that correlates with a given environmental condition (e.g., a noxious stimulus in the proximal environment). Thus, even very rudimentary non-natural information, by Millikan’s and similar views, may qualify as representation.

However, more restrictive concepts of representation may rule out many instances of non-natural information as non-representational. Let us consider just two more restrictive concepts—neither of which, it should be noted, deals explicitly with non-natural information as such. On Lloyd’s view [29], for example, it is insufficient for a physical state to yield some behavioural output (e.g., eye blinking in response to a noxious stimulus) for that state to qualify as a representational vehicle (of the noxious stimulus). This state also has to depend—via multiple channels—on the simultaneous conjunction of multiple events (e.g., receptor events) all responding to the same, single environmental condition (e.g., the noxious stimulus). So, even if each individual channel carries information about the same environmental condition, they do not each qualify as a representational vehicle: “(w)ithout some further constraint, information provides a bad fit with (a) metatheory of representation” [29] (p. 51).

In the case of perceptual representation, according to Schulte [30], constancy mechanisms are needed in addition to the functions of a given system that track some environmental feature by means of processing information. Constancy mechanisms have the function of producing “representational states that covary reliably with certain objective features in the world” based on vastly variable sensory information [30] (p. 128). “(T)heir presence in a sensory system is necessary and sufficient for the system’s being a perceptual system” [31] (p. 413).

These two views suggest that a more prudent approach here would be to leave open the question of whether non-natural information and representation are extensionally equivalent, for additional theoretical constraints and/or mechanisms are required for some neural state to represent X besides just carrying information about X.

It is not always clear that “carrying information” about X suffices for the representation of X. For one thing, some neurocognitive theories simply try to explain whether a neuronal
activity detects or responds to a particular environmental feature without claiming that it represents that feature. For example, the question of whether neurones in the striate cortex are sensitive to the presence of a circle or a vertical line need not presuppose that these neurones represent vertical lines. If natural information by itself is indeed insufficient for representation [3,27,32], it remains unclear in virtue of what that non-natural information qualifies as representation. Is it in virtue of functional factors (e.g., the information being exploitable by the processing organism)? Why is non-natural information always alethically evaluable? These questions are still open, and it is far from clear that non-natural information is a more well-understood category than representation.

3.2. Natural, Sensory, and Endogenous Information

To avoid such potential problems about the nature of non-natural information and to help to determine the applicability of the desiderata below in different explanatory contexts, we suggest distinguishing amongst natural, sensory, and endogenous information. To be sure, these three types of information are not on an equal ontological footing: sensory and endogenous information do not exist in the absence of a cognitive or sensorimotor system. The present analysis does not attempt to carve out the different types of information that are necessary and, supposedly, sufficient for the naturalisation of cognition. Others have suggested additional notions of information—which are on an equal ontological footing with natural information—that are required for such a naturalisation project, including control information [33] and information-as-structural-similarity [34] (p. 76). The present analysis is guided by the types of information posited by neurocognitive explanations. Let us discuss them in turn.

Natural information—as it is typically conceived—is exogenous: it concerns correlations, and often causal relations, between events, features, and states of affairs. “(O)ur brains ( . . . ) process exogenous information about the external environment by transducing physical phenomena (e.g., changes in energy, molecular concentrations, etc.) into sensory perceptions that allow us to generate and maintain a sense of what is happening around us” [35].

Photoreceptors, mechanoreceptors, and other receptors (even in more rudimentary organisms, such as molluscs) transduce different physical features of the environment affecting the organism into sensory information that is (typically) used to guide the organism’s actions. It should, for starters, be clear that natural and sensory information are different. Why?

Even though sensory information can also be classified as being covariational in nature, it is not exhausted by tracking statistical regularities of the environment. Consider just a few reasons, starting with neural adaptation. The responsiveness of sensory cells tends to gradually decrease over time when facing the same stimulus repetitively. Receptors that are repeatedly exposed to smoke, say, may undergo neural adaptation, and thus their activation state may no longer be in a high correlation with fire. Another reason is the noisy environment: one cannot simply assume an optimal sampling of the environmental stimuli by the sensory apparatus. For example, the stochastic nature of reflection by environmental features and photon emission results in a variability in the number of photons sampled by photoreceptors within a given neural integration time [36]. Besides, even setting aside the possible corruption of sensory information by neural noise, sensory receptors are designed to maximise the signal-to-noise ratio for detecting sensory inputs. The photoreceptor, for example, is designed to intensify photon absorption to extract maximum light information [37]. Smoke is correlated with fire whether the latter is small or big, whereas the photoreceptor intensifies, and does not merely covary with, the absorbed photon. Many of the above differences stem from a more basic dissimilarity: vehicles of sensory information are evolutionarily designed to carry that information, whereas cues, as vehicles of natural information, are not. We may, therefore, conclude that sensory and natural information are not equivalent.
The last type of information in this trichotomy is thoroughly endogenous. Whilst sensory information is stimulus-driven, endogenous information can be roughly described as being expectation and/or goal driven. “(O)ur brains also process endogenous information that reflects our current internal homeostatic states, past experiences, and future goals” [35].

Prior information, which plays a key role in the debate on cognitive penetrability (i.e., is perception informationally encapsulated from cognitive information?) and in Bayesian models of cognition, is endogenous. A relatively recent study in cognitive penetrability has provided evidence that “V1 contains specific color information related to (an observed) object even (when) the sensory bottom-up signal is entirely achromatic” [38] (p. 65).

Similarly, V1 neurones were shown to fire on the apparent motion path as though real motion was present, even in the absence of a bottom-up signal (i.e., sensory information) through the retina or through lateral interactions [38] (p. 66). Additionally, binocular rivalry seems to show that complex, abstract information (“two objects cannot simultaneously be in the same place”) may bias low-level visual processes (i.e., switching between the sight of a face and a house in the same visual field). Cognitive penetrability, then, seems to presuppose, under some circumstances, the modulation of sensory information by endogenous information.

Consider another, more radical example of endogenous information that is manifested in hallucinations. Hallucination is sometimes explained in terms of learning, Bayesian inference, and a reliability-based tradeoff between sensory information and prior expectations biased toward high-level priors. Expectation may dominate perception when high-precision prior predictions exert an inordinate influence over perceptual inferences, thereby yielding percepts with no corresponding environmental stimuli [39]. Thus understood, prior beliefs—as vehicles of endogenous information—play an active role in the construction of percepts in the absence of objectively identifiable natural information. It is “(t)he integration of exogenous (i.e., natural) and endogenous information (that) allows us to meaningfully interpret our surroundings, prioritize information that is relevant to our goals, and develop action plans” [35]. In the proposed conceptual trichotomy, natural information is exogenous and supposedly reflects a mind-independent, statistical regularity in the world (but see more on that in Section 4.6) that is the basis for sensory information. Non-natural information is a proper subset of the union of sensory and endogenous information; it refers to representations that can be true or false.

We can now proceed to identifying and defending the desiderata based on this tentative conceptual trichotomy.

4. Desiderata for Cognition-Friendly Theories of Information

In this section, we identify (and defend) six desiderata that are often posited in information-processing neurocognitive theories. These are: (1) the quantifiability of information; (2) the substrate neutrality of information; (3) the sender neutrality of information; (4) information being receiver dependent; (5) some information being non-symbolic, and (6) some information being mistakenly tokened. This list is not supposed to be either fixed—as noted above—or exhaustive: there can be other cognitive-theory-specific desiderata. Our focus is on the more common ones. We describe and elaborate on each of them in turn.

4.1. (D1) Quantifiability

Information should be quantifiable. The shift of psychology, from the stimulus-response paradigm of behaviourism to cognitive science, was partly inspired by information theories that attempted to formalise “information” and provide measures for quantifying it [1] (p. 1415). A very early example can be found in Miller’s work [40] evaluating the limits on the amount of information that people can receive, process, and remember, drawing on information theory. There are at least two main reasons for the importance of quantification in psychological research. The first is that—like in the natural sciences—quantification supposedly ensures objectivity, precision, and rigour, thereby removing any biased influence
by the scientist on the explanandum. The measurable properties of the explanandum are
considered inherent in the phenomenon itself and are not merely imposed by the scientist.
The second reason is that correlational analysis is required to identify effects and constructs
that underlie the measured phenomena [41]. Thus, the quantifiability of information as an
explanatory posit in psychology is desirable.

Quantification is likewise important in cognitive neuroscientific research, which studies
and measures neural information processing. Neuroscientific techniques include single-
cell recordings—tracking the firing of individual cells, fMRI—looking at neuronal activity
at a larger scale, and EEG/MEG—tracking time-locked responses to stimuli, thereby providing
insights into the underlying neural representations. Information in the brain is typically
taken to be encoded by (a) patterns of activity across a single or many neurones (encoding
information by neuronal populations or clusters), (b) the timing of spike trains (encoding
information only in the location of the spike times), (c) the timing or phase of continuous
neural activity (encoding information in the signal’s amplitude), (d) synchrony across a
neural population (encoding information by synchronised groups of neurones), or (e) some
combination of the above [1]. The quantification of information is essential for scientists
to find regularities amongst these patterns, calculate signal-to-noise ratios, evaluate the
optimal neural coding, and identify bounds on information transmission and storage.

Consider two examples in which information is both explanatory and quantified. The
first one concerns the sensory information that spike trains convey about the environ-
ment [42]. Scientists assert that single neurons convey large amounts of information, on
the order of several bits per spike, and signals with more natural temporal correlations are
said to be more efficiently coded. Rieke et al. ask “(h)ow do we quantify the notion that the
spike train of a single cell “conveys information” about the sensory world?” and add that
they are “search(ing) for sharper versions of (such) questions by forcing (themselves) to
adopt a more precise and more mathematical language” [42] (p. 13).

Ultimately, they argue that Shannon’s information theory provides a suitable math-
ematical framework for dealing with questions about information transmission by spike
trains. Insofar as Rieke et al.’s analysis also encompasses endogenous anticipatory signals
or endogenous control signals, both sensory and endogenous information are amenable
to quantification.

Another example concerns spatial cognition in foraging ants. Remembering landmarks
and estimating distances and directions travelled over a specific period (i.e., also processing
endogenous information) are cognitively hard problems. Ants can reduce their cognitive
load by conveying information about the spatial coordinates of distant goals to their
nestmates. Some ant species (e.g., Formica cunicularia) can even switch between different
foraging strategies depending on environmental stimuli (e.g., the size of the available
food sources) and “internal” stimuli (e.g., colony growth). One paradigm for quantifying
such information transfers is based on the “binary tree” model, which requires ants to
send (sensory) information about the sequence of turns they have to take to reach the
perceived food. The model enables the experimenter to measure the ants’ ability to share
directional information with nestmates [43] (p. 1151). The experimenters know the amount
of information (in bits) that should be sent—based on the high correlation between the
food’s location and a specific sequence of turns (thereby forming natural information).
Thus, they can measure the time ants actually spend to send that information. The upshot
is that any notion of information that is not quantifiable is too vague and imprecise to
perform real theoretical work in cognitive science.

4.2. (D2) Substrate Neutrality

Information is neutral with respect to the implementing underlying substrate. The same
information can be conveyed by various physical means (for a critique, see, e.g., Polger
and Shapiro [44]). The proposed trichotomy reveals this desideratum quite straightforwardly: natural information may be conveyed by a variety of physical substrates in nature
(e.g., smoke as a product of a material in combustion or light waves reflecting from an
object). Sensory information is conveyed by electrochemical signals that result from the transduction of stimuli (e.g., light waves or patterns of air vibrations) by sensory receptors. Endogenous information is conveyed by hormones, neurotransmitters, electrochemical activities, etc. “(W)hen someone shouts “Fire!” (substrate-neutral) information flows through a series of distinct information-media, each of which instantiates the information in its own unique way: first the ear drum, then the middle ear, cochlea, basilar membrane, ( . . . ) and, finally, the auditory nerve” [45] (p. 137).

Nevertheless, substrate neutrality—implying some degrees of freedom for implementing a given message—should not be confused with substrate independence [46] (p. 70). “Irrespective of the amount of Shannon information that can be embodied in a particular substrate, what (the signal) can and cannot be about also depends on the specific details of the medium’s modifiability and its capacity to modify other systems” [47] (p. 402). The same message can be encoded by many different signals. In the transmission from a source to a destination, it can be encoded, for example, into an acoustic, electrical, or chemical signal—so long as the underlying medium has sufficient degrees of freedom. Spatial information about a particular object that is conveyed by light waves (which reflect from the object and its surroundings) can sometimes be conveyed, for example, by the reflections of high frequency sound waves (which bounce off that object). (That is, assuming that the receiver is equipped with visual and auditory apparatuses. See also desideratum D3.) However, the information does depend on being implemented by some substrate as its bearer. This idea has led to the inevitable claim about the impossibility of physically disembodied information—particularly in the physics of computation [48,49].

A theory of information that ignores D2 may fall short of providing the theoretical scaffolding for neurocognitive theories that explain, for example, cross-modal sensory integration and combination, or the formation of episodic memories. Let us briefly consider both. Sensory information from different modalities is integrated to influence perception, decision making, and behaviour. “(Q)ualitatively different kinds of information from the various sense organs are put together in the brain to produce a unified, coherent representation of the outside world” [50] (p. 284). Clusters of neurones between sensory-specific areas were found to not only respond to the sensory information of different modalities, but also be capable of integrating these multisensory inputs. Sensory integration enhances and accelerates the detection, localisation, and reaction to biologically noteworthy events. It is also a key asset in signal disambiguation in both animal communication and human speech [51]. This fundamental characteristic of perception and cognition is enabled by the substrate neutrality of information.

Similarly, when we experience the world, our “brain is constantly bombarded by massive amounts of external sensory information which potentially could be encoded and stored into (episodic) memory” [52] (pp. 1198–1199). The binding of different sensory information into a unique, coherent episodic memory likely depends on neuronal activity between the entorhinal cortex and hippocampus. This activity binds temporal information about the sequence of events (“when”), spatial information about the experience (“where”), and the experiential information (“what”). Importantly, “memory retrieval can be cued by all types of sensory stimuli” [52]. The sight, smell, or taste of a particular teacup can be all that is needed to trigger memory retrieval: information about the presence of the teacup can be implemented by different substrates, yet it needs to be physically implemented.

4.3. (D3) Sender Neutrality

A sender should not always be presupposed in the flow of information. The need for this desideratum stems from the classical sender-receiver model in Shannon’s information theory and signalling game theories. The common distinction between cues and signals in animal communication studies helps to defend the claim about sender neutrality. A cue, such as smoke or dark clouds, is “a feature of the world, animate or inanimate, which can be used by an animal to guide future actions” [53] (p. 3). A signal is “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” [53]. Signal exchange amongst organisms presupposes an actual sender that sends information, whereas cues do not.

A sender should, therefore, be distinguished from a source of information. A source of information can be a physical object (e.g., a fallen tree trunk in the wood) or a physical process (e.g., a wave breaking on the beach) that conveys information (e.g., an obstacle in the path in the wood) without any communicatory goals, and may remain completely unchanged as a result. Smoke and dark clouds—as cues—are correlated with fire and rain, respectively, and are, hence, abiotic sources—rather than senders—of information. Ignoring this desideratum is, typically, the result of focusing too much on symbolic information, which presupposes, at the very least, a potential sender. However, information flow in perceptual and other biological systems does not always require a sender. Identifying information flow with communication is too restrictive [17,54,55] and, thus, explaining how information flow is possible in the absence of a sender—particularly, in organism–environment interactions—is an important desideratum.

4.4. (D4) Receiver Dependence

Information flow ultimately depends on there being a receiver. Whilst it may be sender neutral, being receiver neutral takes the edge off of information informing an informee. Where signals are concerned, a sender is part of a special type of informational exchange that occurs when both it and the receiver have co-evolved to interact with each other on a regular basis [55] (p. 583). Where cues are concerned, however, the reaction to the source may contribute to a type of receiver’s response that is beneficial over evolutionary time (ibid, 580–581). “A physical signal has semantic properties only where there is an interest-driven justification for the response it engenders” [16] (p. 96). A receiver is at the centre stage whether information is conveyed by cues or signals.

D4 implies a weaker and a stronger constraint on information. Consider again smoke and dark clouds as cues. They are arguably informative only relative to a receiver that is (a) sensitive to them and (b) can, at least in principle, exploit them [13,27,56–58]. A spatiotemporal correlation between smoke and fire cannot qualify as information to a receiver that is deprived of vision and olfaction. Even if two events are perfectly correlated, but no organism on the planet can detect them (not even humans equipped with cutting-edge technology), why should we say that one event carries information about the other? Thus, the weaker requirement implied by D4 is the sensitivity of the receiver to the physical substrate embodying the information concerned. The stronger requirement, which entails the former, is that the receiver be able, at least in principle, to exploit the information concerned. An amoeba may change its trajectory moving in the direction of a food cue. An adult ape may seek shelter from rain at the sight of dark clouds. A candidate theory of information may adopt either only the weaker constraint or both constraints.

Why is D4 important in the context of cognitive scientific explanatory practices? In short, because in the context of cognitive science, information makes little sense in the absence of an entity to be informed, be that an entire organism or interacting parts in the brain. Where sensory information is concerned, events, objects, and (other) organisms in the world are information sources, and the organism sensing its environment is the receiver. Natural events just unfold in the world and organisms that are sensitive to these events may exploit any extracted information to benefit them presently or in the future.

What about endogenous information exchanged between interacting parts of the brain? Do these parts act alternately as senders and receivers? Hallucination, again, is a paradigmatic example of endogenous information processing that is devoid of any real correlate in the external world. It may be argued, however, that some part of the brain produces that information and transmits it to other parts (and is, thereby, the sender). Despite the many conceptual and technical challenges that Shannon’s sender-receiver model raises for neuroscientific techniques, neuroscientists should adopt the “cortex-as-receiver” perspective “to track the causal dynamics from one area to the next to establish whether a
measured response is indeed information used by the rest of the brain” [1] (p. 1418). Does the firing of a V1 neurone ever cause activity in the MT or V2 areas, for example? “If it does not, it is a difference that never makes a difference. It is not information, even if it correlates with behavior” [1].

4.5. (D5) Symbolic/Non-Symbolic Information

Some information is non-symbolic, whereas other information is symbolic. Symbolic information includes statements, propositions, and sentences (not only in natural language, but also in programming languages and mathematics). It also includes maps, diagrams, and traffic signs. Because information processing in cognitive systems is arguably not limited to the processing of symbols, D5 seems to be a trivial desideratum. Despite the undeniable importance of language for the higher cognition of humans (e.g., remembering sentences is typically easier than remembering sensorimotor patterns), pre-linguistic babies and nonhuman animals process information that is non-symbolic. Of course, fully developed adult humans who are capable of processing symbolic information also regularly process non-symbolic information when sensing and acting on the natural world around them.

This claim is reminiscent of the heated debate—which culminated in the 1980s and 1990s—about whether cognitive processing is symbolic or sub-symbolic. The firings of neurones in vertebrate brains need not involve symbolic tokens, despite claims to the contrary [59]. On the symbolic view, cognitive processing is essentially symbolic: it consists of computing the consequences of enacting propositional attitudes based on inference rules. On the sub-symbolic view, cognitive processing is essentially associationist: spatiotemporally congruent events are associated in the brain by spreading activation patterns. Nonetheless, insofar as—at the very least—some information processing (e.g., proprioceptive or olfactory information) is non-symbolic, the neurocognitive theory concerned should (also) appeal to a theory of non-symbolic information.

Although a detailed evaluation of symbolic information exceeds the scope of this article, let us make some general observations to enable the ensuing analysis of D5. Symbolic reference is often contrasted with iconic and indexical reference. Iconic reference—used, e.g., in simple depiction and pantomime—depends on form similarity between the informational vehicle and its referent. Indexical reference—used, e.g., in pointing and innate forms of communication, such as facial expressions—depends on contiguity, correlation, or causal relations. Symbolic reference, however, is independent of any likeness or physical relation between the informational vehicle and its referent [60] (pp. 393–394). To interpret a collection of pebbles (shaped as “SOS”) as symbolising a call for help, one must also understand social conventions, for neither the form nor the physical makeup of the pebble collection carries this information intrinsically. Symbolic reference depends on an encompassing system of relations within which the formal similarities and/or correlative aspects of the symbolic vehicle are embedded [60] (p. 399). This reference emerges from reflexive relations that symbols have to one another. For present purposes, we take symbolic information to be carried by spatiotemporal detachable signals that are part of a systematic, rule-governed, signalling system (adapted from Fresco et al. [13], p. 562). It depends on the signal’s relations to objects and events in the world, as well as to other signals in the system. Whether or not a signal qualifies as a symbol depends on whether one adopts either a liberal or a restrictive definition of symbolic information.

Whilst in logic, and psycholinguistic theories, for example, the primary focus is on symbolic information, a vast number of research areas in cognitive science study the processing of non-symbolic information. Logic operates on symbolic structures; numbers are added together, and characters are compared and concatenated to form more elaborate symbolic structures. Psycholinguistic theories study the mental processes that are implicated in the acquisition, production, and comprehension of language. The cue-based retrieval theory, for example, accounts for the processing difficulty in language comprehension, and is based on architectures and mechanisms of human memory. The expectation-based parsing theory models classic sentence-processing phenomena using a Bayesian framework to predict
which parts of a sentence will be more difficult to process. The central parsing challenge that these two influential (and other) psycholinguistic theories face is how to incorporate incoming, new symbolic information (phonemes, syllables, morphemes, and lexical items) into a dynamically forming complex representation [61]. Any such theory should provide “an account of what constitutes the input to the mental process—that is, what information is operated upon by those processes” [62] (italics added). Psycholinguistic theories, then, should appeal to a theory of symbolic information.

Nevertheless, other neurocognitive theories study phenomena that are underpinned by the processing of non-symbolic information. Models of animal signalling, for example, are relatively clear cases. Chemical communication in ants and the honeybee waggle dance are not typically analysed in terms of symbolic information (but cf. Gallistel [63], p. 145) who argues that the waggle dance symbolically specifies the direction of and distance to the nectar). The distance to the nectar is correlated with several dance components, including the duration of the sound, the number of waggles, the duration of the wagging run, and the duration of the return run [64] (p. 143). However, unlike symbolic information that may refer to spatiotemporally distal objects, events, or states of affairs, basic animal signals, such as the waggle dance, refer to the here-and-now, driven by the immediate circumstances of the message production [65] (p. 341). We may consider vervet (and other) alarm calls as functionally referential signals that offer important insights into the evolution of symbolic communication in human language. Nonetheless, the notion of information that is used by animal communication scientists to describe these alarm calls is functional, rather than symbolic.

Moreover, theories that explain more complex neural, and cognitive, phenomena appeal to sensory and/or endogenous information that are not characterised as being symbolic. Let us only consider the appeal to “information” in motor control and learning studies. Motor control theories study the production of controlled, adaptive, and automatic movements, as well as the performance of efficient, coordinated, goal-directed movement patterns spanning multiple levels within the nervous system. The relationship between the task and the environment is critical when the cognitive agent selects and enacts specific motor plans. “(O)ptimal performance is achieved by feedback control law that resolves redundancy moment-by-moment—using all available information to choose the best action under the circumstances” [66] (p. 1227). The relevant information includes both endogenous information (e.g., control signals and goal states) and sensory information (e.g., combined visual and auditory information for estimating the position of a stimulus, or proprioceptive information about the location of one’s limb combined with visual information of the limb itself [67] (p. 514)).

Relatedly, motor learning scientists study the complex neural processes during practice or repetition that lead to an improvement in the accuracy and smoothness of movement patterns in task performance. They examine variables that contribute to the formation of motor programmes, the strength of motor schemas, and the sensitivity of error-detection feedback processes. Information available during, and following, each practice or repetition is remembered and forms the basis for motor learning. The main sources of information are the action plan (endogenous information) and feedback (typically, sensory information). Is there any reason to assume that these kinds of information are necessarily symbolic? The following sample of questions—which underlie motor learning research—seems to suggest a negative answer. How are reward signals used to train a strategic process with a nearly infinite action space? How are error signals used to update internal models that map desired goals and the motor responses that are necessary to achieve those goals? How are discrepancy signals used to adjust the relevant movement strategies? [68]. The upshot is that such neurocognitive theories posit the processing of non-symbolic information, and, therefore, require a theory of non-symbolic information.
4.6. (D6) Mistaken Tokening

Finally, information may be mistakenly tokened. The possibility of “mistaken information” clearly exists. Consider illusory and hallucinatory perceptions: they are not veridical, as they do not track the actual state of affairs. There is nothing in the environment corresponding to the mistaken information that the agent processes. Yet, veridical, illusory, and hallucinatory percepts, arguably, stand on an equal cognitive—though not epistemic—footing, insofar as they are all processed in a like manner (for a discussion to that effect see, e.g., Corlett et al. [39], and for an opposing view, see, e.g., Moran [69]). It is, hence, important to consider the production of information that can be mistaken in some cases.

Is it up to the theory of information, then, to specify the conditions under which information is mistaken? Notice, first, that D6 deliberately does not specify a priori whether mistaken tokening amounts to information being false or simply inaccurate. Several philosophers have recently shifted to attributing, at least to perceptual states, accuracy rather than truth conditions [70–73]. Accuracy and truth are related, but have distinct properties, for the latter is binary (at least under classical logic), whereas the former admits of degrees [70] (p. 458). Maps and pictures, for example, are more or less accurate—rather than true or false—depending on their degree of resemblance or isomorphism to what they stand for [71] (fn. 35). Truth conditions, on the other hand, imply that the information concerned asserts that something is the case in a manner akin to propositions or linguistic constructs [72] (pp. 59–60). Hence, whilst it certainly makes sense for some instances of symbolic information (e.g., propositions in logical or natural languages) to be true or false, it is far from clear that non-symbolic information (e.g., an eagle alarm call produced by an infant vervet monkey in response to a bird that is not an eagle) can be alethically evaluable—though it can be more or less accurate.

Three different explanatory approaches to information suggest that a theory of natural information need not specify the conditions under which natural information is mistakenly tokened. On the Dretskean approach, natural information is factive, and, thus, it cannot be erroneous. As Dretske famously put it, “false information, and mis-information are not kinds of information—any more than decoy ducks and rubber ducks are kinds of ducks” [5] (p. 45). It is the representations that fail to carry the information that they are supposed to carry that qualify as misrepresentations [5] (p. 192). Neural informational states that do not properly track the world should, on Dretske’s view, be part of a naturalistic explanation of misrepresentation. Nevertheless, explaining such normative factors (i.e., the misalignment between neural states and the world), on his view, falls outside the scope of theories of natural information per se.

According to recent probabilistic approaches to natural information, such as Scarantino’s [14], information cannot be mistaken for another reason. There is no error if a cue, or signal, carries information that X is more probable, but X does not occur [14] (pp. 439–440). In other words, natural information is non-factive. Recall that, in Scarantino’s theory, the requirement of perfect conditional probability is dropped. The probability of an event occurring can truly be 0.9, even if the correlated event does not occur at a given time. Natural information is simply an incremental change in the probability of an underlying event (e.g., there being fire) relative to some prior probability. (This prior probability is fixed by specific background data—as in Bayesian confirmation theory.) An error occurs if the receiver takes the cue/signal to stand for X when X is not the case. This, however, is an instance of either non-natural information or sensory information.

On a third approach, advocated by Baker [74], natural information is factive, but is based on physical necessity, rather than on laws of nature—as in Dretske’s approach. “Covariance between smoke and fire, between foxes and rabbit brains, and between fundamental particles all share the feature of being invariant under a range of initial conditions” [74] (p. 14). Whilst there are no laws of nature that apply without exception in cases of information transmission between foxes and rabbit organs, for example, there are relationships of physical necessity that are sensitive to initial conditions. Such initial
conditions include the presence of a live fox, patterns of air vibration in the rabbit’s ears, the presence of a working rabbit brain, and the presence of a life-sustaining planet. Even on Baker’s approach, theoretical resources beyond the theory of information are needed to explain how information may be mistakenly tokened in some neural states.

The interim upshot is that organisms clearly make mistakes, and it remains unclear how such mistakes may be accounted for by natural information. Perhaps, “(s)ome mistakes are due precisely to the reception of probabilistic information about events that fail to obtain” [75] (p. 319). So long as there is a receiver of information, there always exists the possibility of a mistake based on that information. However, natural information—even when it is weakly construed—cannot be either false or mistaken. What may be the cause of such mistakes? If we adopt the classical sender-receiver model, there seem to be three options available: the message may be distorted by a noisy channel, the receiver’s decoding procedure may malfunction, or the receiver may misinterpret the (decoded) message. If mistaken information is unaccounted for, the explanatory value of information is unclear.

Sensory and endogenous information are often described in neurocognitive theories as incorrect or inaccurate. The ubiquity of cognitive phenomena in which there is a mismatch between the world and how it is perceived by an organism calls for an explanation of that mismatch. A neurocognitive theory that attributes the mismatch to mistaken information can (and should) explain how that information may have been distorted by noise. The McGurk effect is a clear example of sensory integration in which a perceptual error occurs when one misperceives sounds due to a mismatch between the audio and visual parts of speech. Even motion sickness is sometimes explained by a discrepancy amongst current visual information, vestibular information, and proprioceptive information, based on a temporal comparison with prior information from the immediate past. Nevertheless, it is the relevant theories of information that should specify the accuracy (or truth) conditions of information. The burden of explaining how sensory and endogenous information can be mistakenly tokened lies both with the corresponding theories of information and the neurocognitive theories that appeal to the underlying types of information.

This concludes our outline of the desiderata for cognition-friendly theories of information (see Table 1 below).

### Table 1. A list of identified desiderata and their applicability to three types of information.

| Desideratum                  | Natural Information | Sensory Information | Endogenous Information |
|------------------------------|---------------------|---------------------|------------------------|
| 1. Quantifiability           | ✓                   | ✓                   | ✓                      |
| 2. Substrate-Neutrality      | ✓                   | ✓                   | ✓                      |
| 3. Sender-Neutrality         | ✓                   | ✓                   | ✓                      |
| 4. Receiver-Dependence       | ✓                   | ✓                   | ✓                      |
| 5. Symbolic/Non-Symbolic     | n/a                 | ✓                   | ✓                      |
| 6. Mistaken Tokening         | n/a                 | ✓                   | ✓                      |

### 5. Global Workspace Theory: Which Features of Information Are Posited?

In this penultimate section, we briefly evaluate how one influential theory in cognitive science—the global workspace theory (GWT) of consciousness—presupposes the above desiderata (at least partially; see the discussion below concerning D1). According to GWT, what one experiences as a conscious state, at any given moment, is the global broadcasting of information across an interconnected network of prefrontal-parietal areas and other distant high-level sensory areas [76] (p. 911). Several sensory and other specialised modular circuits compete and cooperate for access to the limited-capacity global workspace, and only the more salient inputs are those that are eventually selected and broadcasted. This processing remains unconscious, until some underlying activity exceeds a certain relevance threshold and ignites the global workspace. When ignition occurs, the salient information is
broadcasted and sustained until it decays and remains silent [76] (p. 912). That information is made consciously accessible to many local processes, including memory, attention, motor planning, and verbal reporting [77]. Despite GWT still being a controversial theory [76], a large body of empirical findings seems to be consistent with this theory [78]. Nonetheless, we simply focus here on the features of information posited by a neurobiologically informed version of GWT—the global neuronal workspace (GNW) theory (GNWT).

How do the localised modular cortical areas and the GNW interact? The localised modules all connect to the GNW, and process specific perceptual, motor, memory, and evaluative information preconsciously [78] (p. 777). The GNW is formed by a large, interconnected network of long-range cortical neurones distributed over the prefrontal, cingulate, and parietal regions with reciprocal horizontal projections to neurones in other cortical areas through long-range excitatory axons [79] (p. 210). GNW neurones typically accumulate information through recurrent top-down/bottom-up loops, in a competitive manner such that only a single representation ultimately achieves a global conscious status. There is, thus, no single brain centre where conscious information is collected and dispatched, but rather a synthesis of multiple processes converging to a cohesive metastable state [80] (pp. 56–58).

Let us evaluate, in order, which features of information GNWT posits, starting with D1. GNWT predicts that consciously available information can be identified with a deeper and more prolonged propagation of information through long-distance connections, as compared with information that remains unconscious. Dehaene et al. report, for example, that some “paradigms afforded a precise measurement of the timing of information progression and conscious access in the visual system” [80] (p. 71). They add that various neuroimaging “data suggest that conscious access causes a major change in the availability of information that is easily detected by a variety of subjective and objective measures” [80] (p. 67). A recent EEG study in humans indexed levels of consciousness using mid-range and long-range weighted mutual information as a measure of information sharing [78] (p. 787). Nevertheless, it seems that though GNWT presupposes that information is quantifiable, its present measurements are mostly indirect. That is, rather than applying standard information-theoretic measures, such as differential entropy, mutual information, or Kullback-Leibler divergence, indirect measures of brain activity are used. Consider, for example, an ongoing international adversarial collaboration that aims to reveal the footprints of consciousness [76]. Participating scientists claim that GNWT predicts that the ignition of the global workspace (i.e., information sharing) is measurable by long-range synchrony between the prefrontal and sensory cortices. Patterns of this information sharing can be approximated by measures of (gamma/beta) synchronisation between the sensory response/intrinsic activity and the evoked stimulus [81]. The upshot is that if the explanatory role of information in GNWT is contingent on that information being measured directly, then this role may be less central then it would otherwise appear to be.

The fact that different types of information are processed in the localised modular cortical areas prior to ever reaching the GNW implies that D2 is likewise assumed by GNWT. The relevant cortical areas are said to process perceptual, motor, memory, and evaluative information. GNWT aims to explain how information across distributed cortical processes can be integrated despite their difference. The hypothesised binding mechanisms are believed to co-select distributed feature representations that are part of a single object, thereby explaining why conscious object representation is usually coherent and integrated [78] (p. 783).

 Whilst D4 is conspicuously posited by GNWT, D3 is only trivially assumed by the theory insofar as some sensory information received originates in the abiotic world. GNWT explains that when one is conscious of some information, different brain circuits have access to that information. Hence, there is an organism that not only receives the information but is conscious of that information. Furthermore, distinct specialised modular cortical areas first receive specific perceptual, motor, memory, and evaluative information from the respective neural subsystems. Then, when competing for access to the GNW, they become
information senders. Likewise, the GNW acts as a receiver when it receives information from the winning modules, and then as a sender that broadcasts that information to other cognitive, sensory, and motor subsystems. Information thus plays an explanatory role in that it is part of a causal chain that may start either in the external world (sensory information) or in the organism itself (endogenous information), culminating in a successful receipt by the GNW. In sum, the receiver concerned is either the GNW that receives bottom-up information from localised modular cortical areas, or any specific modular cortical area that receives top-down information from the GNW.

D5 is posited in various aspects of GNWT. First, the empirical paradigms that are used to test conscious and unconscious information-processing appeal to both symbolic and non-symbolic information. Language masking experiments, for example, test how words that are presented in close spatial and temporal proximity with other visual stimuli sometimes become unconscious. An early such study by Dehaene et al. [82] (p. 757) showed that unmasking words (i.e., symbolic information) enables the propagation of the activation and ignition of a large-scale correlated cerebral assembly. Focusing on non-symbolic, sensory information, a study by King et al. [83] tested how brains encode many features of a visual stimulus, and showed that only task-relevant features (in that case, presence, angle, and visibility) are later maintained during the delay period, even when the stimulus is reported as unseen. Subjects were asked to detect and mentally maintain the orientation of a masked grating, which is clearly non-symbolic. Second, the precise format of information in the GNW remains an open question [84] (p. 166). One possibility is that it reflects the underlying structure of the winning sensorimotor system. Another is that symbolic information is the suitable medium for integrating the output of heterogeneous processes. Last, understanding self-consciousness, in GNWT, may be based on the capacity for recursive thought, which may require, in turn, symbolic capacities [78] (p. 791). The upshot is that GNWT posits the processing of both symbolic and non-symbolic information.

Finally, GNWT also posits D6: effortful conscious processing is error-prone and the communication between brain circuits and GNW is susceptible to noise. First, some hypothesise that a salience network in the GNW monitors the relevance and/or salience of sensory and endogenous information entering the GNW relative to unimportant background noise [85]. Dysfunctional gatekeeping may result in the inadvertent broadcasting of information, thereby leading to abnormal conscious perceptions—as in hallucination. Furthermore, theoretical constructs of signal detection theory are claimed to map onto specific pre-stimulus and post-stimulus states of GNW neuronal activity [78] (p. 791): a noisy internal representation of the stimulus, and a decision threshold corresponding to the ignition threshold in the GNW. Mistaken information that might become conscious is a live possibility according to GNWT. More generally, insofar as any specific global workspace model appeals to the very distinction between message and signal for explaining the possibility of noise, distortion, or mismatch between encoding and decoding, information plays an explanatory role in that model in describing disturbances of consciousness.

By way of concluding this section, we briefly reply to a possible objection pertaining to GNWT as a particular case study. Above we have claimed that “information” is highly dependent on context with respect to the specific neurocognitive theory that uses it. Given that GNWT seems to satisfy all six desiderata, possibly except for D1, it might seem to have been cherry-picked to provide further evidence for these desiderata. However, examining every information-based neurocognitive theory is clearly impractical. Having chosen a different case study that shows that only four (or three) features of information are posited would not have invalidated the remaining desiderata. Rather, it could have shown that “information” plays a lesser explanatory role in that theory as compared with GNWT. Agreeing upon all the desiderata is not an easy matter, as “information” is used differently and possibly inconsistently by extant neurocognitive theories. Nonetheless, dissent about the importance and relevance of the desiderata is a step in the right direction in determining the explanatory work “information” does in specific information-based neurocognitive theories.
6. Conclusions

Information is sometimes only an explanatory gloss rather than a key explanatory construct in understanding cognition; but when information does play an important explanatory role, it is methodologically useful to explicate that role. To that aim, having distinguished amongst natural, sensory, and endogenous information, we have identified and defended six desiderata that information-based neurocognitive theories often posit: (a) quantifiability, (b) substrate neutrality, (c) sender neutrality, (d) receiver dependence, (e) symbolic/non-symbolic, and (f) mistaken tokening. These desiderata can be used to evaluate (1) how competing theories of information fare as a foundation for such neurocognitive theories, and (2) the explanatory role that information plays in a given neurocognitive theory. For example, a perceptual theory that does not appeal to the possibility of information being false or inaccurate in explaining misperceptions or hallucinations is likely less reliant on information as an explanatory construct. To show how central the notion of information might be in some information-based neurocognitive theories, we have briefly evaluated the global workspace theory of consciousness for its appeal to different features of information. Of course, other neurocognitive theories may posit fewer (or, alternatively, even more) features of information. In such cases, the neurocognitive theory concerned would place fewer (or, alternatively, more) constraints on suitable theories of information. Understanding the explanatory role and the precise notion(s) of information used in cognitive science is an important steppingstone in explaining representation.

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Notes

1. Despite the differences between them, cognitive “theories” and “models” are used interchangeably hereafter.
2. For a critique of the prospects of an integrative neuroscience, see, e.g., Sullivan [86]. She argues that the multiplicity of distinct experimental protocols used to examine the same supposed phenomenon provide evidence against this integrative endeavour.
3. We discuss the factivity of natural information further in Section 4.
4. Therefore, maternal hormones provide a mechanism for transferring environmental cues from parents to offspring.
5. An odd consequence of this view is that an activation of the reflex without the stimulus counts as a misrepresentation.
6. One may also argue that other mechanisms (e.g., a simultaneity constancy mechanism) are required when combining multisensory information (e.g., visual and tactile) about a single environmental event (because different kinds of information take varying amounts of time to be processed in the brain).
7. A recent study of V1 and V2 activity in macaque monkeys reports that the “anticipatory signal reflects a nonsensory component of cortical activity that is ( . . . ) not related to stimulus coding or choice behavior” [87] (p. 5199).
8. “Silence may be very informative. This is a peculiarity of information: its absence may also be informative” [12] (p. 88). If so, then silence supposedly qualifies as disembodied information. However, it does not qualify as information per se, but rather as being informative as part of an inferential process that includes other background information [88].
9. For a similar reason, Scarantino, for example, deems natural information “an objective commodity” that is nonetheless “mind-dependent” [14] (p. 432) relativised to potential receivers.
10. Rathkopf similarly argues that if an organism cannot exploit an XY correlation, even in principle, for some biological end, then that correlation cannot be legitimately used to compute the mutual information between events X and Y [58] (p. 324).
11. This view has been contested [89,90].
It remains unclear, though, (a) why cognitive systems should be in tune with such physical necessities and initial conditions, and (b) how physical necessity is grounded if not by a law of nature.

The question of whether consciousness is the cause or rather the outcome of access to the global workspace does not affect our main argument here.

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