Trends in
Cognitive Sciences

CellPress

Opinion

We know what attention is!

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Attention is one of the most thoroughly investigated psychological phenomena, yet skepticism about attention is widespread: we do not know what it is, it is too many things, there is no such thing. The deficiencies highlighted are not about experimental work but the adequacy of the scientific theory of attention. Combining common scientific claims about attention into a single theory leads to internal inconsistency. This paper demonstrates that a specific functional conception of attention is incorporated into the tasks used in standard experimental paradigms. In accepting these paradigms as valid probes of attention, we commit to this common conception. The conception unifies work at multiple levels of analysis into a coherent scientific explanation of attention. Thus, we all know what attention is.

Highlights

Scientific skepticism about attention has run deeply for a century. We are said to not know what attention is despite over 45 000 scientific papers published on attention since 1950.

The theory of attention is shown to be logically inconsistent. Since too many things are said to be attention, the theory faces a dilemma: contradiction or confusion.

Empirical methodology provides a solution, entailing a *common conception* of attention: attention is a subject mentally selecting a target to guide response.

The common conception provides a methodological norm yielding a functional structure built into every attentional paradigm, so something we all accept and thereby know.

The common conception unifies empirical work into an explanatory theory. Attention is typically what we are trying to explain (effect) and is not an explainer (cause).

Attention: important yet problematic

Attention is important. Inattention due to distraction can result in catastrophic accidents [1,2]. Attentional deficits, such as in attention deficit hyperactivity disorder (ADHD), have socially significant impacts on learning and agency [3]. Social media operates in an 'attention economy' where attention is 'harvested' and 'stolen' [4–7]. Radiologists succeed because of skilled visual attention [8–11]. Attention is among the most well-studied psychological phenomena, with PubMed listing over 45 000 articles with 'attention' in the title since 1950. We attend. Attention is real. Yet, somehow, skepticism about attention abounds:

> 'I don't think we know what "attention" is. It's a concept that's so broad and over-used as to be meaningless. There's lots of things people in psychology and neuroscience study that they call 'attention' that are clearly different things.[i]'

> 'To the question, "What is attention?", there is not only no generally recognized answer but the different attempts at a solution even diverge in the most disturbing manner (quoted in [12]).'

Russell Poldrack (2018) and Karl Groos (1896) similarly worry that we do not know what attention is and that too many things are called 'attention'. After a century, these problems remain. Two recent articles capture the *Zeitgeist*: 'No one knows what attention is' [13] and 'There is no such thing as attention' [14]. This suggests massive confusion and disunity in those 45 000 papers.

Why is there pervasive skepticism? As Groos and Poldrack noted, theorists do not agree on what attention is. Many identify attention with different neural mechanisms. Recent papers in the *Journal of Neuroscience* (2022–2023) note that: attention is a mechanism that 'penetrates early stages of perceptual processing' [15], although this might differ between children and adults [16]; it modulates responses in parietal cortex [17]; and attention is among 'key mechanisms' that co-modulate alpha band frequency and amplitude [18]. At a higher level, attention is noted as a gating mechanism controlling entry into working memory [19] or as regulating 'the deployment of cognitive resources to behaviorally relevant items' [20,21]. Attention appears to be many things, yet no one thing likely performs all these functions [22]. Attention is also said to be a limited resource, something that can be quantified [23]. For example, attention is a bottleneck, open more or less, and anomalies within it help explain psychopathy [24].

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Given such disunity, the concept of attention is judged to be useless. We should stop talking about attention! [25]. Instead, I raise a challenge: can we construct a unified theory of attention? Yes. The answer is embedded in shared experimental practice. Countering skepticism, this paper celebrates the science of attention by arguing that unity already exists based on methodological assumptions that every scientist of attention accepts. In affirming a shared experimental methodology, we commit to a single functional account of what attention is, the *common conception* of attention: a subject's attention is the subject mentally selecting a target to guide behavior. Every experimental paradigm for attention is designed around this structure. Accepting these paradigms, every theorist commits to the same conception. Fittingly, William James expressed this account of attention as what we all know. The conception unifies explanations of attention. Because the solution to skepticism concerns concepts and theory, the arguments that follow operate at that level.

We begin by showing that the present theory of attention is logically inconsistent. The problem is not sloppy language use, but cutting psychological reality at its joints incoherently. After demonstrating the theoretical inadequacy of some responses to the problem, we introduce the common conception of attention, showing that it is built into the task structure of the standard attentional paradigms. Thus, by accepting the experimental paradigms, we accept the common conception. Finally, we draw consequences for many explanations in cognitive science that invoke attention. Attention is the target of explanation. It is not an explainer.

World versus word, use versus mention

A major hindrance to achieving unity is the reflexive response that arguments about attention are merely disagreements about the use of the word 'attention'. Yet, complaints that what follows is linguistic quibbling confuse the logical distinction between *using* words versus *mentioning* them. To talk about (*mention*) words, we use quotations, hence 'attention'. To talk about attention the psychological phenomenon, we *use* the word, hence investigate attention (unquoted). We do not have a science of 'attention' (word), which is nonsensical, but of attention the mental phenomenon. Of course, empirical discoveries shape the meaning of 'attention' and, thus, are relevant to semantics. Nevertheless, the present discussion is part of the scientific investigation of biological phenomena, not of words. The topic is attention, not 'attention'. 'Attention' will largely be unquoted (used) in what follows. To dismiss arguments about attention as mere language games is to persist in logical confusion.

The theory of attention is logically inconsistent

Accordingly, the problem that Poldrack and Groos note is worse than linguistic failure. Rather, the scientific theory of attention divides psychological reality incoherently. Whatever a scientific theory of attention comes to, its present incarnation includes the most widely accepted theses about attention. This generates internal contradictions, which we can formally derive. Many theorists assume (i) and/or (ii):

(i) Attention (A) is phenomenon X: $A = X$
(ii) Attention is phenomenon Y: $A = Y$
(iii) Many of these Xs and Ys are distinct: $X \neq Y$
(iv) Therefore: $X = Y$. Contradiction.

Take the two common claims about attention noted earlier: (i) attention, A, is a neural mechanism/process, N, that alters information processing ($A = N$) [15–18,26,27]; (ii) attention is a limited resource, R ($A = R$), a position entailed by literal attributions of more or less attention [21,23,28–35] (Box 1); (iii) but mechanisms/processes use resources and, thus, are not identical to them since cause does not equal effect. Therefore, $N \neq R$; (iv) we derive $N = R$ from (i) and (ii). Contradiction. The theory of attention is internally inconsistent, among the worst results for any

Box 1. Is attention a limited resource?

To demonstrate the difficulty of arguing for identity claims, consider attention (*A*) as a limited resource, *R*, analogous to energy [28]. The language of attention as a resource entails quantifying attention as more or less. There are many limited resources *R* in the brain. For which of these is there a good scientific argument that $A = R$?

Is *R* channel capacity? Donald Broadbent proposed his filter theory of attentional selection because informational channel capacity is limited and, thus, informational selection is required [49]. An appeal to capacity limitations is a salient basis for arguing for the necessity of attentional selection [100]. However, channel capacity as a limited resource has always been taken to constrain attention. It is not identical to attention.

Is *R* perceptual or cognitive load? Nillie Lavie and coworkers defended a load theory of attention [101] (but see [102,103]). One might interpret the theory as identifying attention with load, but again cognitive and perceptual load constrain attention. Attention depends on load. It is not identical to it.

The challenge to any view that $A = R$ is that there is a weaker thesis compatible with the same evidence: *A* causally depends on *R* (see 'Attention is explanandum not explanans' in the main text). Empirical evidence that supports a correlation between *A* and *R* leaves open whether the relation between *A* and *R* is causation or identity. If the former, then *A* and *R* are not identical, as causes and effects are distinct. For all the biological, physical, and informational resources one might assert as identical to attention, the more plausible hypothesis is that the operation of attention only causally depends on said resources. We should not draw a conclusion stronger than warranted by the evidence.

What then of quantitative descriptions of attention as more or less? Odmar Neumann [59] warned of conflating quantitative measures on performance that depends on attention with attention as itself a quantity measured. Quantitative measures reflect properties of performance, such as reaction time, accuracy, or correlated variation in neural response. It is a further inference that attention is identical to a limited quantity. Indeed, the weaker (better) conclusion is that graded performance measures reflect the dependence of attention on gradable resources, such as energy or channel capacity. Thus, for many values of *R*, the more plausible claim is that *R* constrains and, thus, is not identical with, attention.

theory. Note that at no point is 'attention' quoted. We are arguing about the world. (i) and (ii) attempt to carve nature at its joints by identifying attention with distinct phenomena. The theory ends up depicting a world the structure of which makes no logical sense.

Proliferation is not the answer

Perhaps we can avoid contradiction by proliferation*:* attention is of many different kinds. This teeters on being a language game, a linguistic policy doling out to researchers 'attention' with implicit subscripts: 'attention_1', 'attention_2', 'attention_3'... As a policy, it is problematic. Proliferation is opting for confusing terminology. We face a dilemma: contradiction or confusion. Neither is palatable. As we shall see, there is a middle course to safety.

If proliferating attention is to be a scientific hypothesis, it should be an empirical not a linguistic position. It must claim that something in the world, attention, is identical to other things in the world, say various mechanisms *M* ($A = M$) or resources *R* ($A = R$). However, the epistemic standards of science demand powerful arguments to establish identity claims as such claims are among the strongest one can make. Consider the work required to move from Gregor Mendel's observations of genetic transmission in the mid-19th century to identifying DNA as the genetic material (roughly, DNA = genes). The advance occurred not because biologists adopted a linguistic policy of using the word 'gene' to refer to DNA, but from decades of work at multiple levels of analysis culminating in the publication of DNA's structure in 1953 [36,37].

The standards in cognitive science are no less rigorous than in molecular biology. When theorists make causal claims that attention modulates early sensory representations [27,38–40], attention is equated with the underlying cause. What argument establishes to empirical standards the imputed identity claim? It is not clear whether we have the necessary arguments or whether they are adequate. Proliferation then becomes what we wanted to avoid, a labeling exercise rather than substantive scientific inference.

Table 1. Attentional paradigms and corresponding empirical sufficient conditions

Paradigm	Empirical sufficient condition	Key Refs
Attentional blink	If a subject *visually* selects a target (e.g., a distinctly colored letter) in a rapid serial visual presentation of symbols to encode in memory for later report, then the subject *visually* attends to that target	[104]
Dichotic listening	If a subject *auditorily* selects one auditory stream to verbally shadow, then the subject is *auditorily* attending to that stream	[83]
Inattentional blindness	If a subject *visually* selects a target to render a judgment (number of passes, comparing lengths of the arms of a cross), then the subject *visually* attends to that target	[105,106]
Multiple object tracking	If a subject *visually* selects flashed objects in an array to visually track them for later test, then the subject is *visually* attending to those objects	[107]
Posner indirect spatial cueing	If a subject *visually* selects a cued location (e.g., left or right of fixation) to set detection capacities at that location, the subject *visually* attends to that location If a subject *visually* selects a target (e.g., an '*X*') to report (e.g., by pressing a key), then the subject *visually* attends to that target	[108]
Retro-cueing	If a subject *mnemonically* ('internally') selects a cued encoded location to ready response capacities at that location (e.g., to detect a potential change), the subject *mnemonically* ('internally') attends to that encoded location	[109,110]
Visual search	If a subject *visually* selects a target to report its presence, then the subject *visually* attends to the target	[111]

However, there is an intelligible and mundane sort of 'proliferation' that we can highlight by restating many claims about attention in a consistent logical format that emphasizes shared structure. That is, most claims about attention can be rewritten in this form:

S *m*-attends to *T*

Note three places: '*S'* is a subject variable taking as values entities, things to which attention is attributed; '*T'* is a target variable taking as values all possible targets of attention, such as spatial locations, features, objects, propositions, images, time, and so on; finally, '*m*' is not a variable but identifies a position to specify the mode or way of attending and is replaced with an adjectival phrase (e.g., *auditory* attention [41,42] or *top-down visual* attention [43,44], or *internal*, *memory-based* attention [45–48]). For clarity, I will sometimes set '*m*' aside. If we wish, we can construe these modes of attention as 'kinds' of attention.

The logical frame aids the systematic collation of different kinds of attention using *S*, *m*, and *T*. Table 1 identifies the kinds of attention probed in many standard paradigms, expressed through the functional analysis that I argue all scientists are committed to (see 'We all know what attention is' section). Can these different 'kinds' be unified? That is, can attention be shown to be a single phenomenon that can be instantiated in different modes *m* and with different targets *T*?

The textbook account of attention is false

The textbook account of attention, arguably set in motion by theoretical concerns about the need to selectively process information given capacity limits [49], provides a principle unifying all kinds of attention. Dropping the mode marker, *m,* for clarity, the textbook account asserts:

S attends to *T* = *S* selects *T* for further processing

This is presented in textbooks and reviews [50–55]. Unfortunately, it is demonstrably false. Here is one of many counterexamples.

The rods and cones on the retina have a tuning profile. They show differential responsiveness to different wavelengths of light. Given this, the retina selects specific optical information for further neural processing. By the textbook account, the retina is attending to that information. This is false. The retina selects, but does not attend to, light (information) [56]. Formally,

(i) The retina selects information for further processing;
(ii) *S* attends to information = *S* selects information for further processing;
(iii) The retina attends to information.

The argument is logically valid. If the conclusion is false, one of the premises must be. Since (i) is a biological fact, we reject (ii), the textbook account.

Readers disliking this counterexample can generate many others since information processing is everywhere, such as in one's phone or laptop, but attention is not. Alternatively, one can replace the retina in the argument with one's preferred neural basis of selective processing. Neural entities that select information can provide values of '*S*' in (ii) leading to proliferation in the attribution of attention in brain processes (see 'Attention is explanandum not explanans' section). The problem with the textbook account should now be obvious. It is too broad. Many information-processing systems that select information for further processing do not attend. The solution is to be more specific on *what* selects and *for* what purpose. Enter William James.

James got it right: the common conception

James wrote [57]:

> Everyone knows what attention is. *[Attention] is the taking possession by the mind*, in clear and vivid form, *of one out of what seem several simultaneously possible objects or trains of thought*. Focalization, concentration, of consciousness are of its essence. *It implies withdrawal from some things in order to deal effectively with others* (my emphasis).

James accurately captures the phenomenon we routinely experience. In attending, we take possession of targets to deal effectively with them. We select targets for action [58–61]. The subject's selection of a target for behavior is causally substantive in that it explains their production of a relevant response, say their selecting spatial parameters of an object to guide a grasping movement or selecting specific features to commit to memory. Thus, James describes the causal role of attention in a subject's target selection guiding their behavior.

Theorists citing James often leave out 'deal effectively with' [21,51,62–66], but without it, we have only the problematic textbook account. James showed us how to fix that account by narrowing it in two ways: specifying (i) who/what selects and (ii) for what purpose. First, functionally, attention is selection for a specific type of further processing, namely for guiding behavior where behavior includes overt things we do with our body as well as things done in our head, thus including bodily actions as well as mental actions, such as reasoning, recalling, imagining, and so on [61]. The Jamesian account of attention is:

S attends to *T* = *S* selects *T* to guide performance of behavior *B*.

Second, James restricts values of *S* to subjects with minds. Psychological subjects, not their parts (e.g., their retinas), pay attention. This restriction is also enshrined in our methodological commitments (see following section).

Identity is stronger than we need. For cognitive science, the sufficient condition entailed by James' account suffices:

if *S* selects *T* to guide performance of behavior *B*, then *S* attends to *T*.

This is the *common conception* of attention in cognitive science, which gives the general functional form of attention instantiated in each experimental paradigm for attention. Thus, for every specific value for *B* and *T* given concrete paradigms, we instantiate the common conception as specific *empirical sufficient conditions* for each. Salient examples as an initial analysis are given in Table 1, with the mode, *m,* of attention in italics.

Many theorists explicitly endorse the common conception [48,58,59,67–78]. Many others who emphasize *relevant* selection when expressing the textbook account likely intend the common conception [38,40,43,79–82]. In the following section, I argue that we *all* already accept the common conception.

We all know what attention is

In affirming standard experimental paradigms for probing attention, we all agree to the common conception because the functional structure it expresses provides a norm in experimental methodology.

Focusing on top-down, task-driven attention, attention set by task instructions or appropriate training, consider a necessary condition for an adequate experiment on attention. To study attention to *T,* the experimenter must ensure that, during the experiment, the subject attends to *T*. Attention is set through an instructed task requiring the selection of *T.* In a properly designed task, a necessary condition for correct performance is that the subject selects *T* to guide their response. Such a task, in being built around the functional structure of the common conception, allows researchers to monitor attention by measuring parameters of task performance. This general methodological norm on attention experiments provides a standard of appropriate design and criticism. It also guides assessing when neural data are relevant to attention (Box 2).

Box 2. Interpreting neural data

The empirical sufficient condition establishes the task structure in which attention is engaged. Behavioral data are then collected under the aegis of that condition. At the same time, neuroscientists probing the neural basis of task performance and, hence, of attention, will deploy various imaging modalities to extract neural activity correlated with task performance. To show the centrality of empirical sufficient conditions, here, I note that they provide a functional basis for the collection of correlated neural data, namely identifying that to which neural activity is meant to explain (see 'Explaining attention' in the main text).

Furthermore, the empirical sufficient condition is crucial for an appropriate interpretation of those data. Consider the following activity collected by Carrie McAdams and John Maunsell from a V4 neuron in a macaque monkey (Figure I) [112]. Nothing rides on this example. Any data that exhibit a difference in neural activity for some neural substrate between two different task conditions raise the same issue.

Why does the neuron show a difference in activity under the two conditions? There are multiple possible explanations. For example, since what we are seeing is modulation of neural gain, we can in principle generate the same response curves by changing the gain of the stimulus, say judicious increases in its intensity. This is not surprising for neural data underdetermines theory or hypothesis, an old chestnut in the philosophy of science. Life would be much easier if one could read off psychology directly from neural activity. We cannot. Yet, in this case, McAdams and Maunsell identify one curve as the attention curve, the other as the non-attention curve. Why?

Among cognitive neuroscientists, the manipulation to establish an attention curve is straightforward. Either, say with a cue, indicate to the animal subject that: (i) the item in the receptive field of the neuron is the target (attended); or (ii) that it is not, with the cued target being outside the receptive field (unattended). In both cases, we require that the animal select the defined target to guide task performance. In that way, we set the attention of the animal within or outside of the receptive field through manipulation via task instructions built into the empirical sufficient condition. This manipulation justifies labeling the two neural tuning curves as in Figure I. Thus, in setting a structure on the task, the empirical sufficient condition also justifies the link between neural activity and attention.

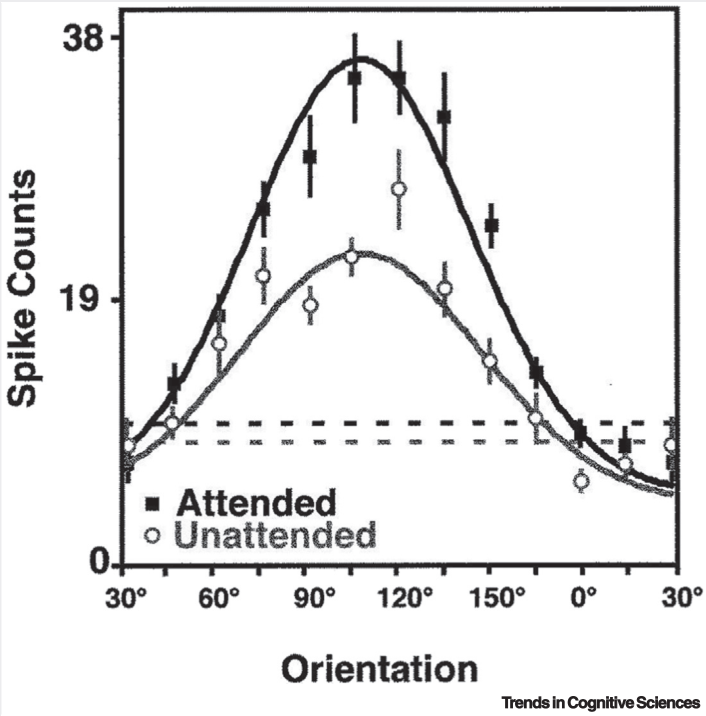

Figure I. Response of a V4 neuron with and without attention. Orientation tuning curves of a V4 neuron in a macaque monkey obtained under conditions of attention (attended) and its absence (unattended). Reprinted, with permission, from [112].

The formal argument is this, where *P* takes as values any standard attentional paradigm, and *S* is any theorist of attention:

(i) If *S* accepts attentional paradigm *P*, *S* is committed to the common conception;
(ii) *S* accepts *P*;
(iii) *S* is committed to the common conception.

The argument depends only on accepting a subset of the standard paradigms (many in Table 1) and, thus, on commitment to current experimental practice in the science of attention. Consequently, we end up at the same starting point, endorsing the common conception that covers the specific empirical sufficient condition for a given paradigm *P*. The conception brings out the shared functional structure that unifies the distinct implementations of it in experimental paradigms: in each, a subject selects some target to guide some behavior.

We can establish (i) for each paradigm at issue in premise (ii). I gave the argument for any arbitrary paradigm *P* in the second paragraph of this section, but I illustrate this here for a concrete case, dichotic listening [83]. In dichotic listening, a different verbal stream is presented to each ear. What identifies one auditory channel as the attended one? The task instruction: select the words heard in one ear to perform verbal shadowing, repeating the words heard. The task is structured as follows:

if *S* auditorily selects words in ear *X* to guide verbal shadowing, then *S* auditorily attends to the words in *X*.

We monitor auditory attention by monitoring the words the subject utters. This analysis can be done for all the paradigms (Table 1; for extended discussion of spatial cueing and visual search, see [84]).

The common conception narrows the textbook account but remains appropriately broad by expressing a functional structure that can be reinstated in new paradigms. Its broadness is also exemplified in leaving open for empirical investigation the implementation and elaboration of selective mechanisms that explain behavior (e.g., [85,86]). Explicating what such selection comes to in detail for specific tasks is part of ordinary cognitive science. The functional structure frames hypotheses regarding the details of the subject's selection for performance in a task. Empirical work within a paradigm refines, and can sometimes alter, the experimenter's initial conception (hypothesis) of what the subject is doing in selection to guide response. Different types of selection will be assigned to distinct levels of analysis. Questions might arise as to whether the observed or imputed selection for behavior is attributed to the subject or merely to a part of the subject. Some cases are clear, such as ruling out the retina. Settling more controversial cases will be part of further empirical investigation in explaining attention.

Attention is explanandum not explanans

The common conception of attention describes a target for empirical explanation. This clashes with a widespread view of attention (*A*) as being some internal neural mechanism *N*, so $A = N$. There are many mechanisms *N* at the center of illuminating explanations in cognitive neuroscience (e.g., divisive normalization). Yet, given that *N* on its own does explanatory work in those domains, why identify *N* with attention [13,14]?

Claims that attention alters neural processing are pervasive in the neuroscience of attention (e.g., [15–18,26,27]). Are there good arguments supporting equating attention with the specific neural mechanism that causes observed effects in neural processing? Relevant evidence begins with an observed correlation between attention, *A,* and the operation of a relevant neural mechanism, *N*. Identity, $A = N$, is a perfect correlation as *N* and *A* cannot dissociate, yet empirically observed correlation is typically imperfect. The challenge to theorists who are committed to *A* being neural mechanism *N* is to explain why current evidence rules out weaker correlations in favor of perfect correlation in identity. Why take attention to be *N* rather than attention being caused by *N?* As identity is among the strongest claims, it requires a powerful argument, which, I submit, has not been given.

To give an example, consider how this contrast between identity and causation plays out in interpreting the biased competition theory of attention. Given too much information, coherent behavior requires a bias to resolve the neural competition for resources needed to process stimuli in the environment. There are many kinds of bias [87–89]. On influential interpretations of biased competition, attention is identified as a bias.

Consider John Reynold's and David Heeger's model of divisive normalization as implementing biased competition [90]. Divisive normalization explains a variety of observed neural modulations

Key figure

Divisive normalization and the Marrian explanatory framework for attention

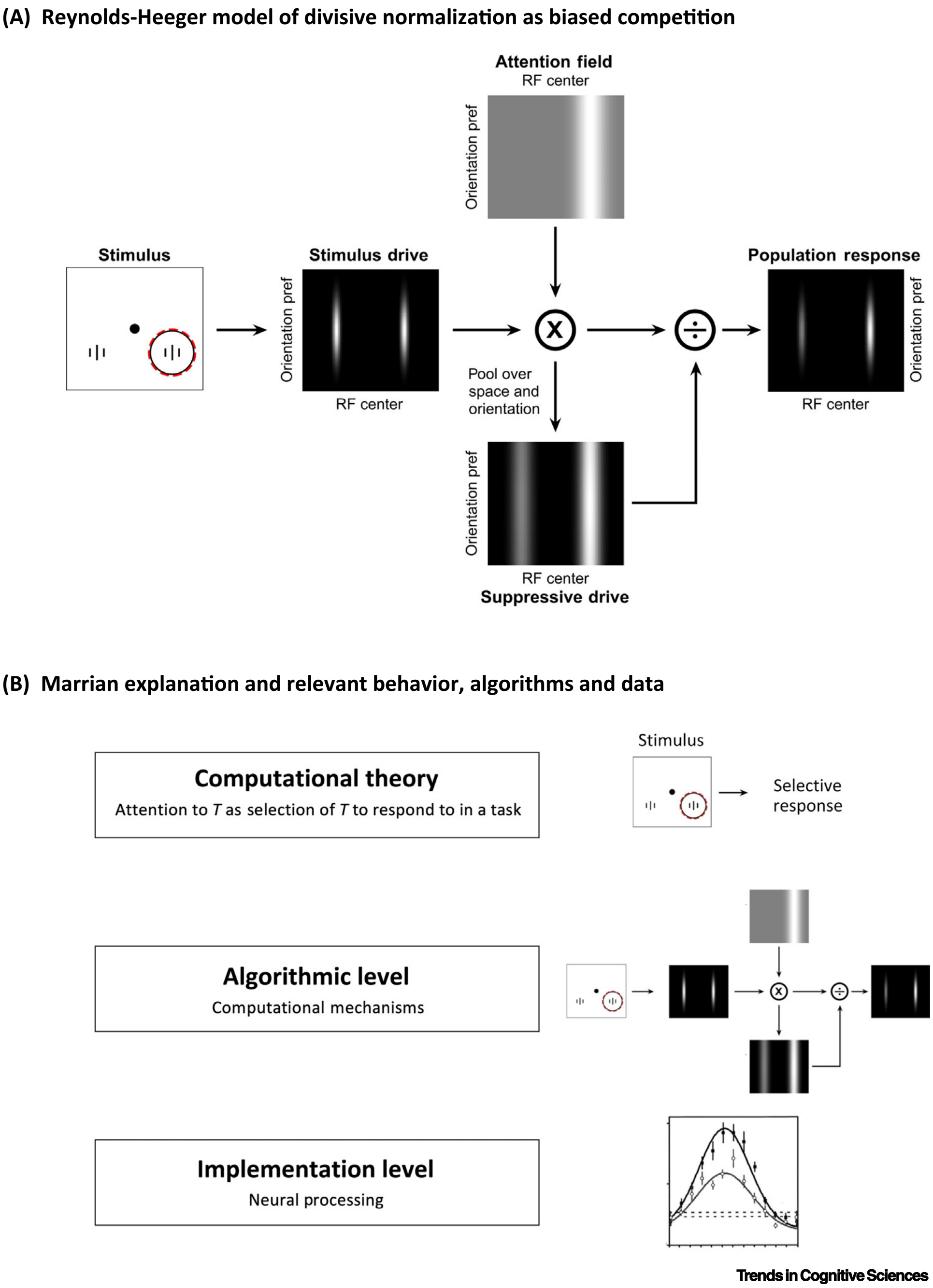

Figure 1. (A) The Reynolds–Heeger model of divisive normalization. The claim that $A = N$ is expressed in the model by identifying attention with the Attention Field, a bias that modulates processing. The Attention Field makes concrete the metaphor of an attentional spotlight as a neural mechanism. Alternatively, the Attention Field might implement a part of the

(Figure legend continued at the bottom of the next page.)

during attention tasks [90–93]. In the Reynolds–Heeger model, the Attention Field is the bias resolving competition (Figure 1A, Key figure). Let attention = Attention Field to explain what it means in the model to say that attention is a mechanism that shifts neural computation. Attention is identified as a specific neural cause, the Attention Field. This implements a neural spotlight of attention.

Heeger and Reynolds need not endorse this interpretation. Instead of taking attention as identical to a causal factor in biased competition ($A = N,$ the Attention Field), they might take the bias to cause, hence explain, attention. In fact, this was Desimone and Duncan's proposal when they explicitly denied the spotlight model in presenting biased competition:

> The approach we take differs from the standard view of attention, in which attention functions as a mental [internal] spotlight enhancing the processing…of the illuminated item. Instead, the model we develop is that attention is an emergent property of many neural mechanisms working to resolve competition for visual processing and control of behavior [94].

Attention is the effect of resolving neural competition across the brain (*cf*. [13,14,95,96]). It is not identified with a mechanism, the cause of resolution, namely the biasing factor. For much of cognitive neuroscience, we explain attention (*explanandum;* effect). Attention is not an explainer *(explanans*; cause*,* see also [13,96]).

Neural biases are an important part of explaining how attention arises. Instead of identifying the Attention Field with attention, we can interpret it as a bias that derives from a task representation encoding information about the cued position as being task relevant. In that way, divisive normalization gives us an implementation of top-down attention that relies on task representation as bias.

I note an important semantical consequence of this argument. The use of 'attention' in causal statements in neuroscience generally adds no useful mechanistic content. This is the primary point of certain skeptics [13,14]. If attention is not a neural mechanism, then statements of the form, 'attention modulates E', where E is a neural effect, saddle us with unnecessary and confusing labeling. Nothing of importance is lost in divisive normalization by interpreting the Attention Field as, say, a signal identifying the task-relevant location given a cue. Crossing out 'attention' in neural explanations [14], we eliminate confusing language.

With the bias construct in place, we can capture bottom-up attention. Riffing on James, top-down attention is the taking possession *of* an object *by* the mind, bottom-up attention the taking possession *of* the mind *by* an object. Selection for behavior remains the common structure. If top-down attentional selection is set by task representations as bias, bottom-up attentional selection in visual attentional capture is set by a different bias, such as a saliency map representing physical

task representation that represents the cued location where the target is likely to be located. Note that the two stimuli (represented in Stimulus) fix two inputs I, which lead to a Selection Problem (see Box 3): which target to act on? (B) Illustration of the Marr-inspired explanatory structure with levels partially filled in. In this example, take a paradigm that requires selection of one target among others to respond to [i.e., one of the two targets in the Stimulus in (A)]. In the computational theory, the common conception as expressed in the experimental paradigm identifies what we are explaining: the subject's selection of a target, here the cued (right) target, to guide selective response to execute the task. At the algorithmic level, divisive normalization identifies an algorithm that partially explains (implements) selective processing of the task-relevant target that contributes to solving the Selection Problem (see Box 3). Normalization is implemented in neural activity. At the implementation level, tuned responses of the sort recorded by McAdams and Maunsell (see Box 2) contribute to neural activity represented in the Input and the Output in the normalization model as when neural gain is modulated (compare changes from the Stimulus Drive to the Population Response). Further empirical details flesh out the explanation, and the common conception organizes work at multiple levels of analysis with attention as explanandum, not explanans. Reprinted, with permission, from [90] (A). Abbreviation: RF, receptive field.

salience, say of a bright flash. This map explains the oculomotor orienting response perhaps in a winner-take-all mechanism [97,98]. Selection of salient stimuli for orienting is involuntary in that its implementation is due to a bias by a saliency map, not by a task representation.

Explaining attention

Emphasizing attention as an ‘effect’ does not exclude it from operating as a cause. This depends on the level of explanation. In notable cases of inattention, in ADHD, or medical expertise, attention, its absence or alteration, causally explains many phenomena. That said, our question is not causal but constitutive: what is attention and how is it implemented in the brain? David Marr provided an explanatory framework for answering the ‘What is X?’ question (e.g., X = vision, [99]).

The common conception takes an important step toward what Marr wanted from a computational theory. It identifies the function of attention as the mind selecting a target to guide dealing with it in a task/action. Descriptions of the subject’s selection to guide behavior in action reflect the structure of biased competition (Box 3). Accordingly, we can construe algorithms and neural implementation as descriptions of mechanisms and processes that explain what attention is as James described it and as our methodology presupposes. The explanation has as initial parts:

(i) Computational theory: attention as selection of T to guide behavior B;
(ii) Algorithmic level: algorithms that explain the mapping of T to B;
(iii) Implementation level: neural implementation of selective processing of T to guide B.

Further levels can be added as needed. Denying that attention is a cause at levels (ii) and (iii) emphasizes that attention is the *explanandum*. It appears at the top level (i), not at lower levels, which characterize mechanisms implementing (explaining) attention.

Box 3. Attention, bias, and action

Action, bodily or mental, as probed in task paradigms, depends on attention [58,59,61,113]. The needed 'selectivity emerged through evolution as a design feature to enable efficient goal-directed action. Such selectivity became necessary as the action repertoire of the given line of organisms that led to humans increased. This means that selectivity is an emerging property arising from myriad underlying processes, and the simple fact that humans (and other species showing selective attention) evolved the way they did, with selective attention being one of many byproducts' [13].

So say Hommel *et al.* in their paper, ‘No one knows what attention is’ [13]. Their point converges with my perspective. The evolutionary perspective highlights the need to solve what we can call a ‘Selection Problem’ at the behavioral level. There is behavioral competition the resolution of which is built on resolving neural competition (see also [114]). Consider the causal network in Figure I.

Treat the inputs, I, as the subject’s psychological states, which represent putative targets for action, and the outputs, O, as including mental responses as well as overt bodily movements. An action, mental or bodily, is an input–output coupling, where the input guides production of output [58]. The problem is that if any action is to occur, ‘selectivity’ of a possible behavior must ensue, say performing one of the four possible actions (Figure I, broken arrows).

Let us say an action is performed, input I_1 guiding output O_2. For example, seeing the shape (I_1) of a target guides a reach-to-grasp movement or encoding the shape in memory (O_2). Now apply the empirical sufficient condition, the subject’s selecting a target, here represented by I_1, to guide response O_2. Thus, attention ‘emerges’ from selectivity entailed by an agent’s action, here visual attention to the shape as visual selection of that shape to guide response. This resolution of behavioral competition parallels, and is built on, the resolution of neural competition.

The generic notion of a bias explains behavioral selection. The bias might be bottom-up, say a stimulus represented by I_1 being physically salient driving a response. It might be top-down, the agent deciding to perform a specific action. Perhaps the bias is acquired from a learned value or past experience (hysteresis and reward [87,115,116]). There are many biases [88], and some have clear ethical significance [117]. Biases resolve behavioral competition inherent in the Selection Problem [61]. Resolving behavioral competition is implemented in resolving neural competition [94], and the figure used to express behavioral competition could be used to coarsely express neural competition [118].

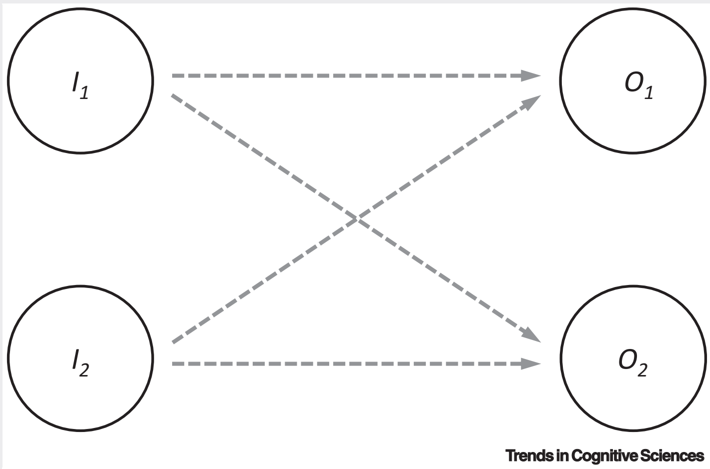

Figure I. Action space as causal network of behavioral options. Simple causal network indicating four possible actions (input–output links as broken arrows) given two inputs (*I*), psychological states, such as perceptual or memory states that represent potential targets, and two output responses (*O*), which can be external motor movements or internal 'movements', such as memory encoding.

The schema unifies work on attention for every paradigm. The computational theory, formulated as a specific empirical sufficient condition, describes a subject's attending to perform task *B* in the subject's selecting *T* to guide the required response. Behavioral and neural data are generated while subjects perform *B.* Computational models (algorithms) are built on the data collected during performance. The task of the paradigm, interpreted through the empirical sufficient condition for *B*, links data and models together (Figure 1B).

This explanatory structure generalizes for every paradigm *P*. We explain attention by focusing on specific tasks, collecting data at multiple scales, and constructing models to generate predictions for further tests. Each level references selection in the task deployed by *P*. The computational theory thereby links these results into a unified explanation through implementation relations linking each lower level to the one above it, ultimately unified by the common conception in descriptions of the subject's attention in action. Thus, in each paradigm, we generate an understanding of attention that begins with the common conception. We know what attention is, and we can explain it.

Concluding remarks

Shared paradigms unify us in a commitment to a common conception of attention. Seeing this only requires recognizing that one already believes the correct account, and so do one's colleagues. What then is attention? A subject's attention to *T* as studied in science is the subject's selection of *T* to perform a task. Where there is broad agreement, skepticism is misplaced. The vast amount of successful research has been implicitly guided by the common conception that renders the theory of attention logically perspicuous, showing how much we have accomplished and how to move forward (see Outstanding questions).

Outstanding questions

How might the common conception illuminate other concepts, such as preattentive processing, early versus late selection, attention as selection for perception, attention as filter or as binding features, and so on? Are these conceptualizations adequate? What is their place in the explanatory theory of attention?

How many levels are needed to generate an explanation for each attention task? What commonalities and differences can we identify once each explanation is sufficiently fleshed out? Might this reveal interesting kinds of attention or mechanisms implementing attention?

What are the principles for dividing levels of analysis and linking them? How do we assign processes to each level and relate processes across levels?

How does the common conception illuminate domains where attention plays an important explanatory role? How might the common conception shed light on the relation of attention and consciousness or attention and working memory? How can it facilitate casting attention as a cause in explanations of skilled behavior, such as in sports or radiological search, or in understanding pathologies of attention?

What are the different types of bias on attention? Can a taxonomy of these biases be given and the relations between each type explained? How might this causal notion of bias illuminate socially significant biases on attention?

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Declaration of interests

None declared by author.

Resources

[i]https://qz.com/1246898/psychology-will-fail-if-it-keeps-using-ancient-words-like-attention-and-memory

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