Perception of happening: how the brain deals with the no-history problem

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Abstract

In physics, the temporal dimension has units of infinitesimally brief duration. Given this, how is it possible to perceive things such as motion, music, and vibrotactile stimulation, that involve extension across many units of time? To address this problem, it is proposed that there is what is termed an "information construct of happening" (ICOH), a simultaneous representation of recent, temporally differentiated perceptual information on the millisecond time scale. The main features of the ICOH are (i) time marking, semantic labelling of all information in the ICOH with ordinal temporal information and distance from what is informationally identified as the present moment, (ii) vector informational features that specify kind, direction, and rate of change for every feature in a percept, (iii), and connectives, information relating vector informational features at adjacent temporal locations in the ICOH. The ICOH integrates products of perceptual processing with recent historical information in sensory memory on the sub-second time scale. Perceptual information about happening in informational sensory memory is encoded in semantic form that preserves connected semantic trails of vector and timing information. The basic properties of the ICOH must be supported by a general and widespread timing mechanism that generates ordinal and interval timing information and it is suggested that state-dependent networks may suffice for that purpose. Happening, therefore, is perceived at a moment and is constituted by an information structure of connected recent historical information.

Perception of happening: how the brain deals with the no-history problem

1. Introduction: the no-history problem

Consider seeing a ball that has been thrown moving through the air or a table just persisting from one moment to the next; hearing a continuous tone or a person speaking; or feeling a piece of fabric being brushed across the skin. For convenience, the term "perceived happening" will be used to refer to all of the things of which these are examples.[1] All of these percepts involve information covering a short period of time and all of them seem quite natural. In fact it is hard to explain how perceived happening can occur at all. In this paper I shall first attempt to explain why that is the case, and then propose a general information structure that makes it possible.

If it is acceptable to divide the temporal dimension into past, present, and future then, at a given present moment, whatever is to the past and to the future of that moment does not exist. So how wide is the dividing line between future and past? The shortest time scale recognised in physics is the Planck time, which is 10^{-44} s (t'Hooft & Vandoren, 2011). To put this in perspective, the period of a light wave, the time it takes light to travel one wavelength, is about 10^{-15} s (t'Hooft & Vandoren, 2011), which is 29 orders of magnitude longer than the Planck time. The temporal dimension in the space-time manifold is a series of Planck time units. That defines the time scale of the present. If we take one Planck time unit as marking the present moment, at that moment no other Planck time unit exists.[2] That is what will be called the no-history problem. No history exists. The Planck time unit, and the no-history problem that is entailed by that, is a plain physical fact, not appreciated by us because we never perceive things that way.

Suppose that someone throws a ball through the air. Imagine a single moment, defined as a single Planck time unit, in the flight of the ball. A very short exposure photograph would be an acceptable way of representing that moment. It is inexact because it would encompass many Planck time units, but it will suffice to make the point. The photograph would show an unblurred image of the ball in mid-flight. Every moment after the moment captured in the photograph was, at the time of the photograph, in the future and had not happened yet; every moment before the moment captured in the photograph was, and remains, in the past and is gone. From the photograph alone, it would not be possible to deduce the history of the object and its motion: it could have been thrown on a parabolic trajectory, or it could have been tossed straight up in the air, or it could have been dropped from a crane. That illustrates the no-history problem. The time 1 ms ago is gone, just as surely as the time 10 years ago is gone. If perception conformed to the reality of physics, at best perception would consist of a mere succession of present moments, one at a time, each of infinitesimal duration and each immediately lost without trace and succeeded by another. There would be no perceived happening - no perception of motion, change, or persistence, just what is the case in that one unit of time. Yet we perceive the motion of the ball, something that encompasses many moments, as if it were the most natural thing in the world. So how does the brain do it? That is the central issue for this paper.

The no-history problem implies that, for any perception of happening or change or persistence to occur, information about the recent past must be retained and integrated with the most recent available information. There are of course many kinds of temporal integration in perceptual processing. To give just one example, visual brightness is a percept that emerges from summation of input information over a period extending up to some hundreds of milliseconds (Aiba & Stevens, 1964; Raab, 1962; Stevens & Hall, 1966). But those are specific, localised processes. For the brain to deal with the no-history problem, there must be some kind of general, organised retention of all information in perception, and that organised retention of information must have features that serve to support all perceived happening, under the broad definition given earlier. That is, there must be an information structure, existing at a moment, that integrates information about a short period of time, and that constitutes perceived happening. Perceived happening is not, and cannot be, distributed over a series of objective moments. It is a representation of a series of moments at one moment. It is the emplacement of the most recent available perceptual information in a context of retained information about recent history. The main aim of this paper is to elucidate the general form of this information structure and to make a case that, without it, there would be no perceived happening.

Having information about present and recent past there at the same time might seem to generate the opposite problem to the no-history problem, a situation where information about multiple moments is experienced as there all at once. In that respect, the job of the proposed information summary is the opposite of temporal integration. It is temporal differentiation: pieces of information being distinguished and ordered by temporal labelling. Thus, information in the proposed information summary is temporally differentiated by means of timing information, and also linked to generate a coherent and appropriately ordered body of information about recent happening. Temporal differentiation is necessary to avoid the problem of a disorderly pile-up of information about different moments in the representation. This will be explained more fully in the sections to follow.

It might seem that describing percepts of happening as information summaries entails a loss of information. In fact, what is being proposed here is the opposite of that: a contemporaneous, integrated, temporally differentiated representation of information about a brief span of time enriches perception in a way that circumvents the no-history problem and allows percepts of what is going on that encompass recent history as well as newly incoming information. This will also be further explained in the following sections.

For any readers who may be uncertain about this, this is not a philosophical proposal. It is a scientific hypothesis, it is subject to test by the usual methods and standards of science, and it needs to be consistent with what is known about perceptual processing. To see how the concerns of science and philosophy diverge on this topic, see Dainton (2008).[3] It may help to say briefly what this paper is not about. It is not about timing, time perception, or duration perception. One or more timing mechanisms may be necessary for the information structure of perceived happening, but timing mechanisms by themselves do not account for perceived happening. And the proposed information structure integrates perceptual information on the sub-second scale. This excludes, for example, research on topics that has been interpreted as supporting the hypothesis of a subjective present on a time scale of about 3 s (Pöppel, 1997, 2009; White, 2017; Wittmann, 2009, 2011). It also excludes research on event segmentation in psychology and neuroscience, which is research on how perceivers spontaneously segment sequences of actions into discrete events separated by boundaries (Altmann & Ekves, 2019; Ben-Yakov & Henson, 2018; Bilkey & Jensen, 2021; Richmond & Zacks, 2017; Zacks, Speer, Swallow, Braver, & Reynolds, 2007). Stimuli presented in studies of event segmentation often have durations of minutes, and events tend to be segmented on a time scale of many seconds (White, 2017).

As a final introductory note, there is an ineluctable explanatory gap in any account of how the human brain deals with the no-history problem. The finest temporal differentiation in the human brain is probably on the microsecond time scale (Grothe, 2003) and, for most information being processed in the brain, on the millisecond time scale. For the remainder of this paper, the term "moment" with reference to information in the brain should be understood as approximating to the millisecond time scale. But a millisecond is many orders of magnitude longer than a Planck time unit. A single neural spike lasting 1 ms has a duration of almost countless numbers of Planck time units. There is some prospect of solving the no-history problem at the millisecond time scale of brain activity, which is the aim of the present paper, but there is no prospect of going any further down the scale towards the Planck time unit than that.

2. The information construct of happening[4]

Given the no-history problem, how is perceived happening generated? Take the example of the thrown ball, and suppose that 500 ms of the ball's trajectory is presented as a stimulus. At input to the eye, the temporality in the stimulus is there: input (in the form of light waves) enters the eye for 500 ms. That might seem too obvious to be worth stating, but it is stated in order to contrast with what happens in the generation of a percept of the ball and its motion. The no-history problem applies: when the last light wave from the stimulus presentation enters the eye, all of the previous history of the stimulus is gone and does not exist any more.

At some latency after onset of the stimulus, a percept of the ball as an individuated perceptual object with binding of its perceived features emerges (Kahneman, Treisman, & Gibbs, 1992). Some information about happening forms part of this perceptual object - velocity information, for example. That is not enough for perceived happening because velocity at a moment tells us nothing about what was going on before that moment. Some information about the recent history of the ball must be preserved. Without that, the past could be anything and we are in the position implied by the no-history problem, not knowing what the ball was doing or even if it was there at all at any time before the current percept. Therefore, a representation of velocity now is not sufficient for perceived happening. There must be retained historical information that is integrated with current perceptual information.

What form does the historical information that is involved in perceived happening take? As we have seen, a single photograph of a ball in flight does not suffice for its motion properties to be ascertained. Could the problem be solved by taking a series of photographs of the ball at frequent intervals during part of its trajectory? If all the photographs were available for inspection at once, that would make it possible to infer the trajectory of the ball. But there are three problems. One is that each photograph is an isolated individual momentary set of information. The situation would somewhat resemble that of the patient studied by Zihl, von Cramon, and Mai (1983) who suffered from akinetopsia: her visual world consisted of a series of static images lacking any motion information, updated at infrequent intervals, so that she was unable to judge simple practical matters such as when to stop pouring tea into a cup. Perception moving from one snapshot to the next would be essentially the same, though on a shorter time scale: one very brief static image of how things are after another with no connection between them. The second problem is that, because of the no-history problem, only one snapshot would exist at a time. This is worse than akinetopsia, because the patient with akinetopsia could at least remember the previous image once a new one had appeared, so that she had some awareness of things having changed. Perceptual experience would comprise a rapid series of extremely transient static images existing one at a time, with each one lost as soon as the next one appeared, which is clearly not the case. The third problem is that, even if the photographs could be preserved as a set, information about their order of occurrence would also be needed: without that, the sequence of events would not be clear. So the perceptual equivalent of a mere series of momentary photographs would not be sufficient to engender perceived happening.

Those problems show that, to engender perceived happening, there must be a contemporaneous body of information about recent history with (i) some form of temporal differentiation so that there is a perceived order of things in time, and (ii) some form of integration that binds the information together over time without abolishing the temporal differentiation. That integrated, temporally differentiated body of recent historical information, the proposed solution to the perceived happening problem, will be called the Information Construct Of Happening (ICOH). Its main features will be briefly described here, then treated in more detail in subsequent sections. Perceived happening comprises the following: temporal information that marks all informational components of the construct with their distance in time from the (perceived) present and their ordinal relations, so that relations of temporal adjacency can be represented (section 3); information about what is going on with perceptual features and objects at a given moment in time - this is vector information (section 4); information that links the vector information across temporal co-ordinates in the representation to construct a coherent representation of what is going on on the time scale of the ICOH - this is connectives (section 5). The information in the ICOH is partly in the perceived present (i.e. products of higher perceptual processing) and partly in informational sensory memory (section 6). Information transferred from the perceived present to informational sensory memory is subject to decay and transformation into semantic form, so that much of perceived happening comprises semantic markers with vector information, connectives, and temporal information (all as summarised above) attached to them.

3. Time marking

It is proposed that information in the ICOH is marked with temporal information that subserves the functions of temporal differentiation and connection. That enables the representation of perceived happening as an organised, connected temporal sequence. It is first necessary to say what it is for something to be marked with temporal information. A time marker is the semantic encoding of some temporal feature that is attached to perceptual information about features or objects. Semantics concerns meaning, so the term "semantic" is used to denote the idea that a time marker is an abstract but meaningful piece of information. In perception, an example of semantic information would be object identification or categorisation, such as perceiving the stimulus "A" as a letter of the alphabet rather than just a visual shape. In the present context, therefore, a time marker is a meaningful item of information attached to a perceptual feature or object. Time marking is not a novel idea (Dennett & Kinsbourne, 1992; Herzog, Kammer, & Scharnowski, 2016) but its proposed role in perceived happening is novel. A possible mechanism for time marking of happening information will be discussed in section 7.3. Here, the kinds of time markers and their role in the ICOH will be elucidated.

It is proposed that all information about features, objects, vectors and connectives in the ICOH is marked with temporal information of two kinds, ordinality and temporal distance information. The latter will be considered first. Temporal distance concerns how long ago a given state of a feature (including vector information and connectives) occurred, relative to the most recent perceptual information, not relative to events in the outside world. In effect, if information in the perceived present is designated as t^0 in a co-ordinate system, historical information is marked in accordance with its temporal distance from t^0, as t^{-1}, t^{-2}, etc. These abstract designations are used because the temporal resolution of the information is uncertain and probably variable. (In this usage the designations denote co-ordinates in a kind of map, not arithmetical power functions.) The main point is that they are semantic time markers that accomplish the function of temporal differentiation, informationally locating features on the temporal dimension.

But the age of a piece of information in isolation is not sufficient: relational information is also important. An item of information is registered as before another and after a third, and that is part of what binds information into a coherent representation of happening. Thus, the second kind of temporal information in the ICOH is ordinal information. Information at adjacent times must be represented not just as times with different co-ordinates but as ordered and connected: not just t^{-1}, t^{-2}, t^{-3}... but t^{-1} *immediately after* t^{-2} *immediately after* t^{-3}... Perceived happening requires representation of temporal ordinality and temporal distance for every item of information in the representation, to make an integrated, coherent, temporally differentiated body of information.

It could be argued that temporal ordinality is implied by temporal distance information. For example, if there is information that event A occurred at time t^{-1} and event B occurred at t^{-2} then it can be inferred that B occurred before A by one time unit. But the inference (or some processing equivalent of it) does need to be made, otherwise the ordinal information will not be there in the representation. If there is only temporal distance information then A and B will be represented as each occurring at a certain time but not as temporally related to each other. A spatial analogy might help. Two chess pieces, a white knight and a black bishop, occupy different squares on a chess board. It is possible to register the square occupied by the knight and the square occupied by the bishop without registering the spatial relation between them. Additional cognitive work is required for that. For example, the knight might be in a position to take the bishop, but the chess player still has to work that out. So, temporal distance and temporal ordinality information must both be specified as informational components of the representation, because there can be information about one without information about the other.

Thus, we do not directly perceive or experience or have any direct contact with time itself. Our entire experience of time is in the form of time marker information in the ICOH, plus whatever temporal information there may be outside the ICOH; an example might be duration information on the supra-second scale. The ICOH represents all surviving recent information as connected over time. Perceptual objects are identified and bounded across time as well as across space, and the temporal boundaries on a perceptual object are marked by time distance and ordinality information; e.g., this stimulus is a perceptual object that begins at this temporal co-ordinate and ends at that one. It might be possible to construct a perceptual object existing at a moment and no longer, without the ICOH. But to perceive that object as existing across even a small amount of time, the time marking information in the ICOH is required.

4. Vector informational features

The content of a particular body of information at a particular location in the ICOH includes what will be called vector informational features. "Vector" is a term with many meanings and applications but the basis for its use here is the definition given in the New York Public Library Science Desk Reference (Barnes-Svarney, 1995) as "A quantity that has magnitude and direction" (p. 312). In physics, force, velocity, acceleration, angular momentum, and torque are examples of vector quantities. In the present application the term is taken a little way beyond its conventional definition in physics and is used to refer to any kind, rate and direction of change information attached to a perceptual object or one of its features at a moment in perception. For example, there could be vector information about a rotating object that specifies the direction and rate of rotation at a moment in the object's recent history; or there could be information about rate of change in an auditory tone's pitch. It is proposed that every perceptual object and every identified feature of a perceptual object is accompanied by vector informational features.[5]

At what level does vector information apply in the present account? Taking vision as an example, vector information can be attached to any component of a perceptual object and to the perceptual object as a whole. If we take the example of a ball that has been thrown, vector information can specify velocity for the ball (as a perceptual object) as a whole. Vector information also applies to each identifiable feature of the ball. The colour of the ball might vary across its surface; to the extent that that variation in colour can be perceived when the ball is in flight, vector information could apply to each perceptibly different colour on the ball, specifying what change, if any, is going on with that colour at a given moment. This applies to all perceptible features of the ball. This implies that the ball, as a perceptual object, encompasses a great deal of informational components, many of which are vector components. The level of resolution in vector information is set ultimately by perceptual discrimination thresholds, because that is what determines the level of resolution in the object representation.

Vector quantities are not confined to the lowest level of resolution in perceptual analysis. Take the example of a group of several dots moving on a computer screen. Each dot might be perceived as a separate perceptual object, so vector information would be applied to a single dot as a whole and to each of its identifiable features. If some or all of the dots share motion properties then they might be perceived as a single object in motion, a perceptual Gestalt, in accordance with the principle of common fate (Wagemans, Elder, Kubovy, Palmer, Peterson, Singh, & von der Heydt, 2012; Wertheimer, 1923). If that happens, then the composite object could be a unit for application of vector information, specifically information that applies to the Gestalt object as a whole and does not differ across its components. Thus, there could be a single velocity representation for the entire Gestalt object as well as velocity representations for the individual dots. The vector information for the Gestalt object can survive the elimination of one dot or the addition of a new one so long as the Gestalt percept itself survives. If it terminates, then only the vector informational features for the individual dots remain. Even higher levels of unitisation of motion information may occur, as for instance in radial motion of multiple objects and optic flow (Gibson, 1950; Graziano, Andersen, & Snowden, 1994; Johansson, von Hofsten, & Jansson, 1980; Mueller & Timney, 2016; Strong, Silson, Gouws, Morland, & McKeefry, 2017). This example of motion perception, therefore, shows that vector information may be attached to any level of unitisation of perceptual information.

5. Informational links between vector information: connectives

Vector informational features are not enough for perceived happening. A value of a vector informational feature for a perceptual object at t^{-1} and a value for the same feature of the same object at t^{-2} are just two separate vector informational features. For perceived happening, they must be bound together. In effect, something must say that this feature at one temporal co-ordinate became this feature at the next temporal co-ordinate. The information that binds features across adjacent temporal co-ordinates will be called "connectives" (a neologism that is used to avoid unwanted connotations of the term "connections").

A parallel can be taken with spatial information in perception. At the level of a single object such as a ball, the component features of the ball are integrated in a way that includes information about their spatial relations. At a given moment, for example, this patch of yellow might be spatially represented as to the left of and adjacent to that patch of red. This spatial relation information is necessary for the ball to be a coherent perceptual object. Multiple objects are located by informational markers in a spatial representation (Eichenbaum, 2017; Meyerhoff, Papenmeier, & Huff, 2017; Pylyshyn, 1989), which yields a coherent informational structure that defines objects in relation to each other and to the space (the informational representation of space) in which they are located. So it is with temporal information. Successive moments in the history of a perceptual object or feature are located by informational markers in a temporal representation, and bound together by connectives to make a coherent informational structure that charts the changing (or non-changing) state of the object across its history.

A vector quantity of zero for some feature does not mean that there is no vector, it means that no change is taking place in that feature. Mere persistence of some feature without change - that is, with a vector quantity of zero - is as much part of perceived happening as change in features is. Thus, for an object such as the keyboard in front of me, all of its features may have a vector quantity of zero, and all of those vector quantities of zero are linked by connectives across the available information about the keyboard in the ICOH: that is the percept of the keyboard as merely persisting from one moment to the next, with no change occurring.

Functionally, a connective is the linkage information that says that this feature at this temporal co-ordinate is linked to this feature at the adjacent temporal co-ordinate, and it registers the change or lack of change in the vector information for the feature between those co-ordinates. Connectives mark persistence and change; time markers (see section 3) only mark temporal ordinality and adjacency.

Take the example of a stimulus presentation involving two brief stimuli, a red square and a blue square, presented at the same spatial location with a short temporal gap between them, the whole presentation lasting, let us say, 200 ms.This is illustrated schematically in Fig. 1. The stimulus is perceived as initial blank screen, red square, blank screen again, blue square, blank screen again; and this includes information about onset and offset of the stimuli. The red square is perceived as a perceptual object: considered as a whole, there is a vector informational feature marking its onset, a vector informational feature for it at each moment of its presentation, and a vector informational feature marking its offset. (The same could be said for each of its features, but here the object will be treated as a whole.) What makes the red square an object that persists over a certain span of time is the set of connectives between each of its successive representations: onset happened, then persistence with no change (repeated for as many moments as there are), then offset happened. How does that connected sequence relate to the blank screen before and after the stimulus presentation? Part of the answer involves markers for spatial location, which are not the concern of this paper. The relevant part of the answer is the time marking information. Time markers locate the red square and the blank screen and the blue square in a temporal context that specifies duration and ordinality. Thus, the red square is perceived as occurring after a blank screen and before the blue square because the information about them a set of time markers that define their temporal relationship. In that way information in the ICOH incorporates distinctions between different, successive perceptual objects, but also the essential continuity of perceptual experience, to the extent that information about successive objects is retained. All of the information is there at a moment of time. Changes in the information that is in the ICOH from one moment to the next are not perceived happening: perceived happening is the set of historical information existing at one moment. It cannot be otherwise, because of the no-history problem.

Figure 1 illustrates this stimulus presentation sequence in such a way as to show what information is necessary for perceived happening across the time span of the presentation. Fig. 1(a) shows the objective time course of events. When the final blank screen is in the present, all the previous events are in the past and gone. Fig. 1(b) shows in a very simplified and schematic form how the information that constitutes perceived happening for the whole stimulus sequence would be represented in the ICOH. The information shown there exists at a moment in time. The perceived present lags some way behind objective events because of processing latencies (White, 2020) but the time marking information identifies it as the present, and then perceived happening for the stimulus sequence is attached to that. The temporal co-ordinates shown in Fig. 1(b) mark duration, ordinality, adjacency as general features of the experience of time, but connectives mark the connected history of individual perceptual objects and features, superimposed on the temporal co-ordinates.

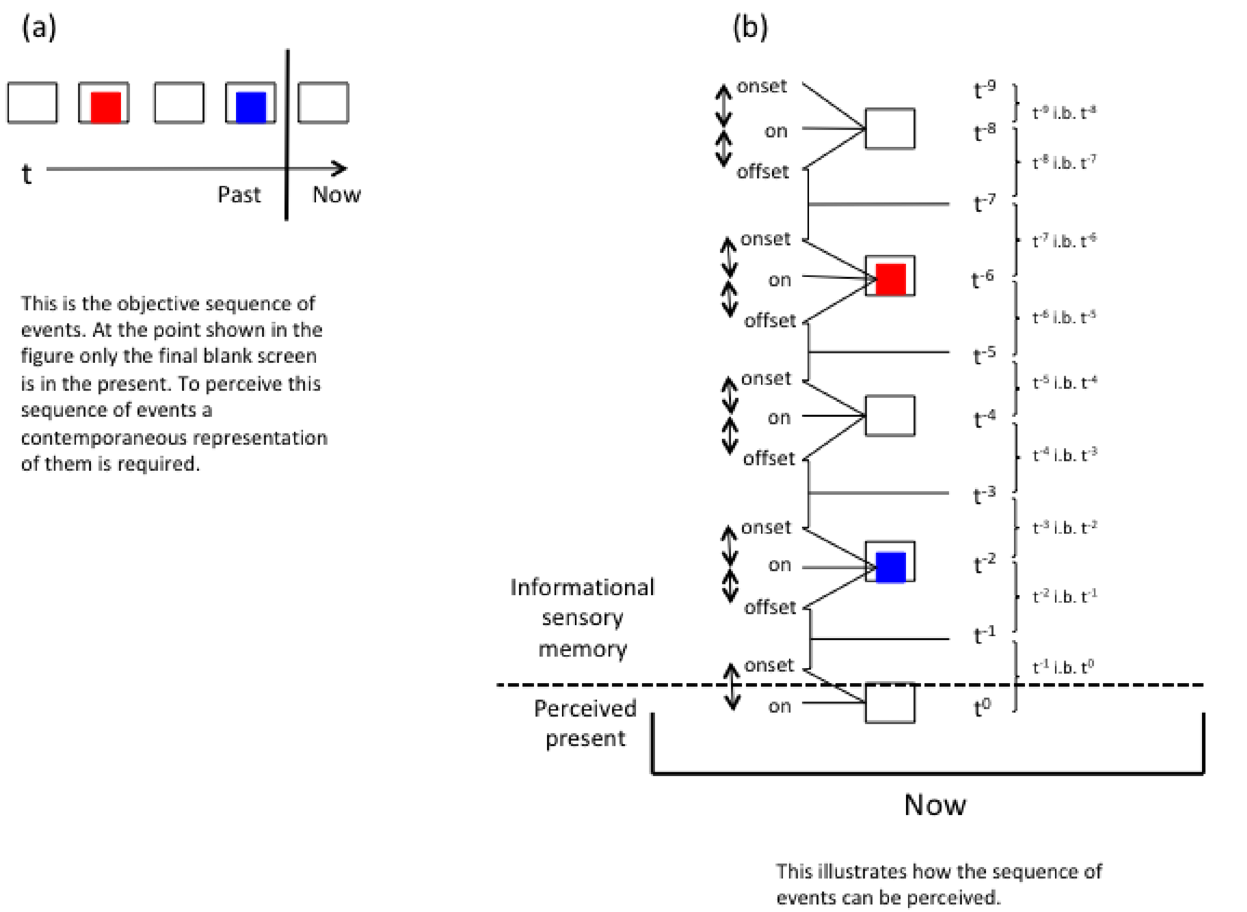

Figure 1: Schematic depiction of the ICOH. (a) shows a hypothetical stimulus presentation of a red square followed by a blue square with blank screen before, after, and between. The presentation takes less than 1 s. At the moment labelled "now", only the final blank screen is in the present and everything preceding that is in the past. The no-history problem applies: what is in the past is no longer available to perception. (b) Schematic informational representation of the sequence of events in the ICOH. All of the information is active at the same time. Labels from "t^{0}" to "t^{-9}" are abstract markers of time distance. Labels from "t^{-1} i.b. t^{0}" to "t^{-9} i.b. t^{-8}" (where "i.b." = "immediately before") indicate ordinal temporal relations. The words "onset", "on", and "offset" are simplified vector informational features. The duration of the "on" state would be specified in the representation but is not given in the figure. Double-headed arrows are abstract representations of connectives, tying the whole body of information together. Offset of one event and onset of another coincide in time so, although they are represented separately in the figure, they occupy the same time co-ordinate and there is no connective between them. The current state of the blank screen is in the perceived present, all other

information is in informational sensory memory. The whole of the ICOH as shown exists at a moment of time, labelled "now" at the bottom. At the next moment the information content will have changed a little. Decay and transformation of information into semantic form are not depicted in the figure. Many additional vector informational features and connectives are not shown for the sake of simplicity.

Figure 2 illustrates a different occurrence: instead of an object stationary at a location in space, a dot moving across a computer screen. Figure 2 depicts a simplified informational representation of the dot's motion. The figure depicts time in the ICOH along the y-axis, as in Figure 1, and the three spatial dimensions are collapsed into one along the x-axis. Vector information for the dot's velocity is represented by single-headed arrows. Connectives are represented by double-headed arrows linking successive representations of the dot. The dot has just disappeared from the screen so there is no representation of it at t^0. As in Figure 1(b), all the information in Figure 2 is there at a single moment in time.

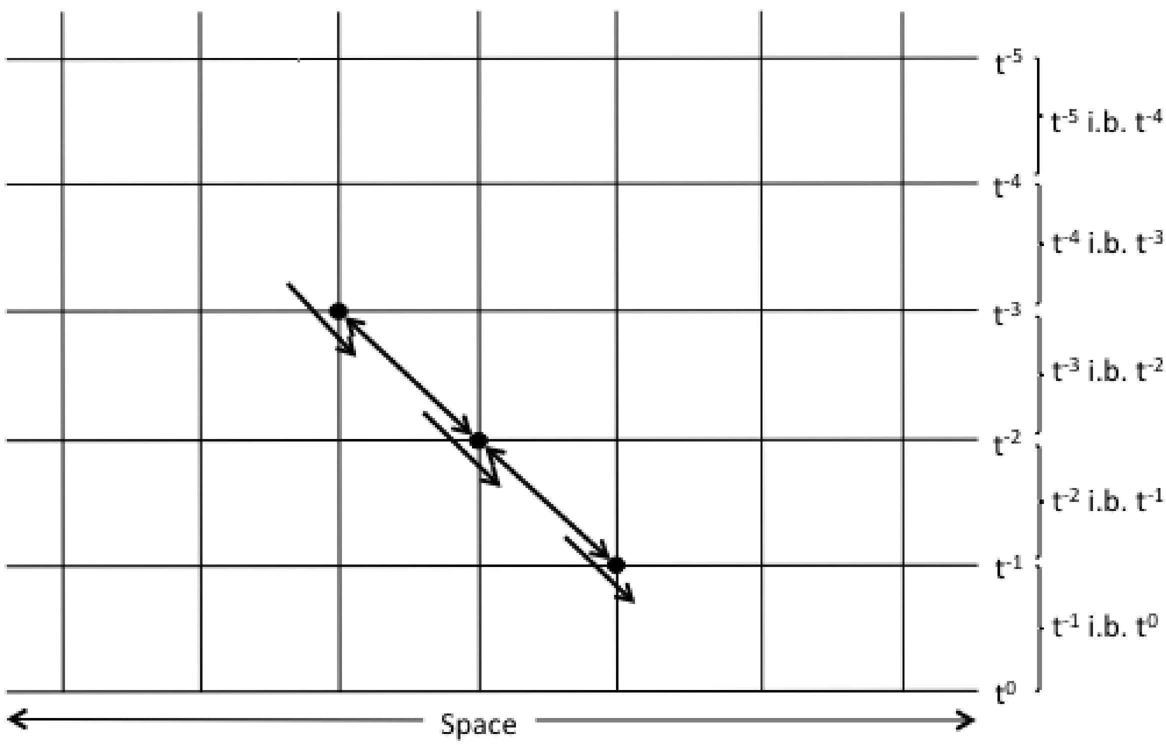

Figure 2. Schematic depiction of perceived happening for a moving dot. The y-axis represents the temporal co-ordinates in the same way as in Fig. 1(b). The x-axis is a collapsed representation of the three spatial dimensions. Single-headed arrows represent vector information for the dot's motion at each temporal co-ordinate. Double-headed arrows represent connectives

for the velocity vectors, linking them together to make a coherent representation of the dot's motion. The space/time framework appears to be a lattice but this is a representational convenience for the purpose of making room for the vector and connective information. The spaces between the grid lines have no meaning. All of the information shown in the figure exists at a single moment in time.

Even in the example of a single dot in motion, this looks like a lot of information, but all of it is necessary. The perceptual world is indeed organised and coherent over space and time, and this can only happen because there are informational markers of space and time that make it so. As information ascends to temporal co-ordinates more distant from t^0, so decay and transformation to a more semantic representation occurs. This will be discussed in section 6.

Could there not be a connective from a representation of the dot, say at t^{-2}, to the same spatial co-ordinate at the previous time co-ordinate, t^{-3}, or to the next one, t^{-1}? The answer is that there is a connection between those co-ordinates already, and it is the ordinal information shown at the right side of the figure. As was stated earlier, the time markers indicate ordinality and adjacency, in effect saying that the place where this object is now was empty at the previous moment. The connectives between successive representations of the object say more than that, specifically that the value of a given vector for that object or a feature of it changed (or stayed the same) across those two moments. Connectives link the history of perceptual objects and features, whereas the temporal co-ordinates locate objects and features ordinally in time but do not link them in the way that connectives do. That, perhaps, is the difference, informationally speaking, between perception of happening for an object and mere perception of the passage of time.

Figure 2 may give the impression that the space and time markers are a fixed grid with perceptual information superimposed on it, but that is not the case. The time markers are continuously created just as the particular perceptual information located in the ICOH is, and they should be envisaged as attached to perceptual information, not as if they were a set of co-ordinates running along the side of the representation. They are presented that way in Fig. 1(b) and Fig. 2 to make it easier to see what is there. The spatial component of the ICOH is updated as the perceiver's location, head orientation, and gaze direction change. We cannot move around in time or look at different temporal locations, so the temporal component of the ICOH is less adjustable, but it is still neurally instantiated and still updated at every passing moment. Thus, at the moment after the one depicted in Fig. 2, the entire representation of the dot and its motion will have moved up by one time co-ordinate. This continues, until it eventually leaves informational sensory memory or decays.

The ICOH does not do any processing of its own. It is just a repository for perceptual information generated elsewhere in perceptual processing. The ICOH preserves perceptual information for a short time, marking its progression through to temporal locations increasingly distant from the perceived present and linking it to new perceptual input with connectives.

To summarise, this is the key proposition: *perceived happening at a given time is the collective set of vector informational features in each of the temporal co-ordinates within the ICOH and connectives between corresponding vector features at adjacent temporal co-ordinates in the ICOH*. Functionally, a connective is the linkage information that says that this feature at t^{-n} corresponds or relates to this feature at t^{-n-1} and registers the change or lack of change in the vector information for the feature between those co-ordinates. The vector informational features, the connectives between them, and the time marking information are what distinguish the ICOH from a store comprising a collection of snapshots (or their auditory equivalent).

6. The ICOH integrates information in perception and informational sensory memory

6.1 The perceived present and the t^0 co-ordinate in the ICOH

In White (2020) it was proposed that the perceived present is not a moment in time but an information structure comprising an integrated set of products of perceptual processing. Specifically, it was proposed to be a very short-term (< 100 ms) and very high capacity holding area for perceptual information. All and only information in the perceived present carries an informational time marker identifying it as "present". Thus, although the products of perception lag behind outside reality because of processing latencies and transmission times, it seems as though the present is being perceived as such because all of the information in the perceived present is time marked as present. In terms of the ICOH, the perceived present is the t^0 co-ordinate.

It is not proposed that <u>all</u> products of perceptual processing enter the perceived present. As a hypothetical consideration, a stimulus that occurred 200 ms ago that has a processing latency of 200 ms and a stimulus that occurred 300 ms ago that has a processing latency of 300 ms would both enter the perceived present at the same time, even though they objectively occurred at different times. Errors of synchronisation do occur (Halliday & Mingay, 1964; Moutoussis & Zeki, 1997a, 1997b) but there is also evidence that perceptual asynchronies can be corrected or recalibrated (Chen & Vroomen, 2013; Corvelyn, López-Moliner, & Coello, 2012, 2015; Heron, Roach, Whitaker, & Hanson, 2010; Parsons, Novich, & Eagleman, 2013; Roach, Heron, Whitaker, & McGraw, 2011; Rohde, Greiner, & Ernst, 2014). That raises the possibility that some perceptual information might be entered into the perceived (or remembered) past, not the perceived present; that is, it is time marked as in the past. The role of recalibration and resynchronisation mechanisms in determining the content of the perceived present at any given moment is an important issue but lies outside the remit of the present paper. For present purposes, what matters is that all information in the perceived present is marked as "present", and it functions as the t^0 co-ordinate in the ICOH.

A given piece of information will only be designated as at t^0 very briefly. After that it is in effect successively redesignated as at t^{-1}, t^{-2}, and so on. But where are t^{-1}, t^{-2}, and so on? The answer proposed here is that the information so marked is held in informational sensory memory.

6.2 Informational sensory memory and the ICOH

Informational sensory memory is a store of information (or a set of stores, one for each modality) on a time scale up to approximately 1000 ms, though that may differ between modalities (Anderson, 1960; Auvray, Gallace, & Spence, 2011; Bliss, Crane, Mansfield, & Townsend, 1966; Coltheart, 1980; Darwin, Turvey, & Crowder, 1972; Gallace, Tan, Haggard, & Spence, 2008; Loftus & Irwin, 1998; Sligte, Vandenbroucke, Scholte, & Lamme, 2010). The capacity of visual sensory memory is possibly about four times greater than that of working memory, though different studies have yielded different estimates (Averbach & Sperling, 1961; Estes & Taylor, 1966; Sligte et al., 2010; Sperling, 1960). Information entering sensory memory decays rapidly to the capacity of working memory (Haber, 1983; Sperling, 1960). As the name would suggest, informational sensory memory is a post-categorical store that includes semantic information (Bhardwaj, Mollon, & Smithson, 2012; Clarke & Mack, 2014; Coltheart, 1980, 1983; Greene, 2007; Sligte et al., 2010; Yeomans & Irwin, 1985), and there is evidence that visual information in informational sensory memory is represented in nonretinotopic co-ordinates (Öğmen & Herzog, 2016).

It is proposed that informational sensory memory is the home of all information in the ICOH other than what is in the perceived present. If that is the case, then informational sensory memory should be capable of holding the kinds of information postulated to account for perceived happening; that is, the vector and connective information that constitute perceived happening, and the ordinal and temporal distance information that provide temporal differentiation for information in the ICOH. There is evidence that temporal order information can be held in informational sensory memory (Smith, Mollon, Bhardwaj, & Smithson, 2011). Stronger evidence for retention of information about happening in informational sensory memory comes from research on multiple object tracking. The problem in tracking multiple moving objects is not just that of retaining information about the motion history of each, but also judging that this object now corresponds to that object then, despite changes in location. Shooner, Tripathy, Bedell, and Öğmen (2010) proposed that the basis for object tracking might be object motion information stored in visual (informational) sensory memory. They presented stimuli of multiple moving objects followed by a cue to report motion direction of one of those objects with a variable delay from termination of the stimulus. They found a decay curve closely matching that found in the experiments on visual sensory memory by Sperling (1960), an exponential decay function with most of the decay occurring in the first 250 ms. Performance stabilised with cue delays of 1000 ms and longer, and the authors attributed that to transfer of information to short-term memory. Reports were more accurate if one object was cued for report than if participants had to report on all objects. This is termed a partial-report advantage, and a similar partial-report advantage, but for static stimuli, was the original evidential basis for the proposal of a visual sensory memory store (Sperling, 1960). Narasimhan, Tripathy, & Barrett (2009) found that detection of deviation from a straight line trajectory in the presence of distractors was influenced by memory for the recent history of the trajectory, with performance declining to a low level if the cue to partial report was presented 300 - 400 ms after the change. This also indicates memory for object motion decaying on the time scale of visual informational sensory memory. Although this evidence does not speak directly to the proposals about vector information and connectives and their roles in perceived happening, it does show retention of information about happening on the time scale of informational sensory memory, and that is consistent with the hypothesis that the ICOH is housed in informational sensory memory.

The distinction between sub-second processing and working memory is marked not just by decay of information but also by selectivity in retention of information and transformation to other representational formats. For example, the transition to short-term memory is marked by selective retention of semantic information and, in the case of speech stimuli, loss of most syntactic information (Sachs, 1967, 1974). More importantly for present purposes, it also marks a transition from what is subjectively regarded as perception to memory (Block & Gruber, 2014; Wittmann, 1999, 2011, 2013). This is an indication of a change in the kind of processing that occurs. In short-term or working memory, happening is remembered, not perceived.

The research on multiple object tracking is, therefore, consistent with the hypothesis that the ICOH operates on the time scale of informational sensory memory and represents both temporal and happening information. To be more exact, at any given moment, there is an informational representation covering a time scale up to ~1000 ms, representing what has happened over that span of time, with greater decay in the information that has been there for longer, and with temporal differentiation in terms of temporal distance and temporal ordinality.

6.3. The visual trail problem

It was argued in the previous section that the historical information in the ICOH covers approximately the last 1000 ms of perceptual information. If we again take the thrown ball as an example, that seems to imply that there should be a visual percept of the last 1000 ms of the ball and its motion: that is, retention of perceptual information on a time scale of ~1000 ms implies that there should be fading perceptual trails documenting recent history on that time scale. In fact the proposed preservation of recent historical information in the ICOH seems to imply that all perceptual features in all modalities would have informational trails that would interfere catastrophically with ongoing perception. Clearly, perceived happening is not like that. Under some presentation conditions visible smears or streaks do occur (Burr, 1980, 1981; Marinovic & Arnold, 2013), but these have been interpreted as visible persistence in the retina or early cortical processing (Farrell, 1984; Sakitt, 1976; Yeonan-Kim & Francis, 2019), not as percepts of happening, and are in any case of shorter duration (~120 ms) than would be expected of trailing or smearing in the ICOH. Visible trails do appear in some rare forms of palinopsia, though the nature of the malfunction that generates them remains obscure (Gersztenkorn & Lee, 2015; Horton & Trobe, 1999), but the rarity and specificity of the phenomena in such cases merely serve to underline the absence of trails and smear in normal perception.

In experiments on visual sensory memory, static stimuli of brief duration are presented and there is evidence for a persisting but rapidly fading trace of the visual information (Sperling, 1960). Typically, the visual field is blank before and after the stimulus presentation, so in effect there are no subsequent stimuli that would mask the trace of the experimental stimuli, as a backward masking stimulus would do (Coltheart, 1980; Di Lollo, Lowe, & Scott, 1974; Di Lollo, 1980). Now consider again the trajectory of a ball that has been thrown. If the observer tracks the ball in its flight, the input information about the ball arrives at the same retinal location for as long as it is tracked. In that case, the fading trace of information about the ball at a given moment would be masked by subsequent input information about the ball to the same retinal location. However, visual information about the recent history of the ball's motion is represented spatiotopically in a spatio-temporal map of the visual world (Öğmen & Herzog, 2016;

Zimmermann, Morrone, & Burr, 2014) and that is the level of representation proposed for the ICOH. That being so, one would expect a visual trail for the ball across its recent history in the spatiotopic representation, and this generalises to all of perception. How, then, to explain the evident absence of such trails?

There is evidence for active deblurring in vision, possibly involving masking or a transient reduction in sensitivity to luminance changes (Bedell, Tong, & Aydin, 2010; Burr, 1980; Marinovic & Arnold, 2013; Scharnowski, Hermens, Kammer, Öğmen, & Herzog, 2007; Tong, Patel, & Bedell, 2005; Westerink & Teunissen, 1995). Marinovic and Arnold (2013) found that deblurring operated on "trailing edges of moving elements moving into a zone... ~60 ms after the element's leading edge had occupied the same position" (p. 52). This is much shorter than the time span of historical information in the ICOH, and it shows that deblurring is a phenomenon of early perceptual processing, prior to entry of information into the ICOH. It is likely that the same is the case for backward masking. Deblurring applies only to visual perception of moving objects but backward masking applies in principle to any kind of visual stimulus. Moreover, there must be equivalent mechanisms in other modalities. In audition, for example, there is evidence for sensory memory in which information can persist for more than 1 s (Darwin et al., 1972), but auditory perception is not obviously cluttered by recent auditory events. When listening to music, for example, the currently perceived note is not cluttered by persisting auditory information about whatever notes occurred in the preceding second or so.

If deblurring and masking mechanisms prevent the perceptual world from becoming cluttered with persisting sensory information on the time scale of sensory memory, what exactly is it that persists in the ICOH? Informational persistence in sensory memory is post-categorical and corresponds to semantic representation of the stimulus (Coltheart, 1980). We have seen already that informational sensory memory can hold information about object motion, which establishes that it is capable of supporting perceived happening. So it can be argued that the information that supports perceived happening is semantic information as well, subject to informational persistence, and that is why visible trails do not occur.

Consider an example. Lappe and Krekelberg (1998) argued that, for a visual stimulus comprising successive flashes separated by a temporal gap, the flashed stimuli are not perceived in the temporal gap but a position signal for them could still be present: "the position signal is available for comparison with other position signals, but not for direct perception of an object" (p. 1447). Thus, the surface visual features of the flash are not maintained in the temporal gap between flashes, but semantic information, in this case in the form of a position signal, is maintained and can still do useful work. Vector information in semantic form could be selectively retained in a similar way; indeed, the position signal is a component of happening information, indicating where and when a particular event happened, and attached to surviving semantic information about the event. It can be understood as existing at temporal co-ordinates in the ICOH that identify when as well as where the flash occurred. Perceived happening, then, is semantic information attached to visual object or feature information: it is there in the form of meaning, semantic representation, but it is not visible (or audible, etc.).[6]

It is important to bear in mind the complex, integrated nature of that information. Some of that complexity and integration is illustrated in Fig. 1(b) (manuscript p. 17), which represents a snapshot of a moment in the ICOH. The information content at all temporal locations other than t^o is predominantly if not entirely semantic; admittedly the visual nature of Fig. 1(b) means that it is not well equipped to depict this fact about the information in the ICOH. Components of Fig. 1(b) above t^0 (the current percept) represent the persisting information about happening with whatever state of informational decay it has reached at that moment: vector information for the components of the stimulus presentation at each successive temporal co-ordinate in the ICOH, connectives that integrate all the vector information over successive temporal co-ordinates, and temporal distance and ordinality information. All of that is semantic information and all of it persists, subject to decay, on the time scale of informational sensory memory. The fact that perceived happening is comprised of semantic information explains why the perceptual world is not cluttered with recent histories of visual, auditory, and other information. The current percept of the ball in flight is accompanied by a semantic trail, not by a visual one.

That hypothesis implies that there should be a selective information bottleneck at entry to sensory memory, specifically a bottleneck at which visual information is lost and semantic information largely continues. There is evidence that is consistent with this (Jacob, Breitmeyer, & Treviño, 2013; Öğmen, Ekiz, Huynh, Bedell, & Tripathy, 2013). Jacob et al. (2013) presented a visual prime followed by another visual stimulus with an onset asynchrony (SOA) ranging from 0 to 2,000 ms. They found evidence for three stages of prime processing: one with a maximum at SOA = 133 ms and declining thereafter, a second with a maximum at SOA = 240 ms declining to an asymptotic minimum at 720 ms, and a third with a maximum at SOA = 1,200 ms and declining thereafter. They interpreted the first stage as corresponding to visible persistence, which has previously been found to have a duration of ~130 ms (Di Lollo, 1977, 1980; Di Lollo & Bischoff, 1995; Shioiri & Cavanagh, 1992). More relevant for present purposes, they interpreted the second stage as corresponding to entry to informational sensory memory. The study by Jacob et al. (2013) showed that that occurs at the end of a rapid decline in information, consistent with the hypothesis of a bottleneck between perception and informational sensory memory selectively favouring semantic over visual information.

7. Discussion

The main purpose of this paper has been to outline the general properties of an information structure that would deal with the constraints of the no-history problem, enabling the representation of what is going on outside the organism (and even inside it; Craig, 2009) in the form of a connected set of information about recent times, on the millisecond time scale. To overcome the no-history problem, there must be a *contemporaneous* representation of a short span of time in the brain, and it must be such as to generate perceived happening. Such information is obviously vital and fundamental to the needs of any mobile organism: the need to co-ordinate action with ongoing environmental events will suffice as an example of its importance. Indeed, it is possible that information about models of planned actions or actions in progress is represented in the ICOH, because actions are inevitably temporally extended. The present proposal hypothesizes a general functional architecture that could form a basis for more detailed models, or indeed for refutation. There are many issues that would require further analysis but space limitations preclude proper consideration of them in this paper. Four will be briefly considered: the alternative hypothesis that the no-history problem is effectively solved in local and low level perceptual mechanisms, the alternative hypothesis that temporal object correspondence could be a solution to the perceived happening problem, a possible neurophysiological mechanism for time marking, and the issue of research evidence.

7.1 Can local mechanisms deal with the no-history problem?

Could it be argued that the no-history problem is effectively addressed by local mechanisms for detecting change? An example would be the Reichardt detector, a low-level visual motion detector (Adelson & Bergen, 1985; Burr & Thompson, 2011; Clifford & Ibbotson, 2003). The simplest form of the detector would involve three neurons, two of which (A and B) respond to luminance changes in their receptive field. If a luminance change passes over A and then B, A is activated and inhibits B, which as a result does not fire in response to the luminance change. If a luminance change passes over B and then A, B is activated and does not inhibit A, which therefore also fires. The successive firing of B and A activates the third neuron C, which thereby functions as a detector of luminance change in a particular direction. Thus motion, which is extended in time, is registered at one time because of the physical nature of the mechanism. Are mechanisms of this kind sufficient to deal with the no-history problem? Although low level mechanisms might contribute to perceived happening, none can account for it altogether for several reasons.

1. The Reichardt detector has a specific job to do, which is local motion detection, so there would have to be equivalent low-level detectors for every kind of happening that can be perceived in all modalities.

2. Low-level motion detectors are not adequate even as accounts of motion perception. There is evidence for at least two kinds of motion detectors (Burr & Thompson, 2011) which operate in different ways and sometimes give rise to conflicting information. A pertinent example concerns the continuous wagon wheel illusion (Arnold, Pearce, & Marinovic, 2014; Piantoni, Kline, & Eagleman, 2010; Purves, Paydarfar, & Andrews, 1996; Simpson, Shahani, & Manahilov, 2005; VanRullen & Dubois, 2011; VanRullen & Koch, 2003; VanRullen, Reddy, & Koch, 2005; VanRullen, Zoefel, & Ilhan, 2014). With a stimulus presenting continuous motion, such as a sunburst pattern on a disc rotating around a central pivot, motion in the opposite direction to or strongly divergent from that in the stimulus can be perceived. VanRullen et al. (2014) pointed out that the illusion of reverse motion occurs despite the fact that low level motion processing is still encoding the veridical direction of motion: therefore, the low level mechanism does not account for the perceived happening in that case. As another example,

deficits occur in biological motion perception in the absence of deficits in low level motion processing, in patients with parietal lesions (Battelli, Cavanagh, & Thornton, 2003). These examples suffice to show that perceived happening, of the sort that is of concern here, cannot be reduced to the products of low level processing. At least some perceived happening is associated with high-level and more global processing, at the level of individuated perceptual objects.

3. Change detectors of any kind do not account for the perception of persistence (e.g. a stationary object undergoing no change).

4. Change detectors do not account for the binding of perceived happening across events. Take the example of two brief flashes of light with a short temporal gap between them. In perceived happening the whole stimulus sequence is integrated into a coherent representation of happening. It says not just that this object now is the continuation of that object then, but that the onset, continuation, and offset of a visual flash, the onset, continuation, and offset of the absence of the flash, and the onset, continuation, and offset of a second flash localised at the same spatial co-ordinate, all form a connected temporal series. This cannot be accounted for by local, low level mechanisms. This is perhaps the fundamental issue. Multiple kinds of change detectors may operate locally and at low level, but the products of such mechanisms are isolated items of information about change. The focus of the present account has been on integration, most particularly integration across time, with vectors and connectives as key features of that integration. A single mechanism that accomplishes all of the integration of information that is required for perceived happening is a more parsimonious explanation than multiple different kinds of detectors and, if well enough designed for the task, can explain how the whole of perceived happening is bound together.

In summary, the advantage of the ICOH is that it can encompass all sensory modalities and all kinds of change, that it is a product of high-level perceptual processing with information represented spatiotopically, that it can represent mere persistence without change, and that it binds events and series of events across connected temporal co-ordinates, generating perceived happening and the ongoing flow of events in perception.

7.2. Does temporal object correspondence solve the perceived happening problem?

In the example of the thrown ball, the ball perceived now is also perceived as the same ball along the path of whatever historical information about it is available. That requires, at minimum, the representation of continuity of existence of the ball across the moments of its available history. There has been research on temporal continuity of perceptual objects. Suppose a flash of light is presented, immediately followed by a second, identical flash of light at a nearby location. Are these two flashes perceived as a single object in motion or as two different objects? Or suppose a stimulus with a given set of properties is briefly presented, immediately followed by a stimulus with a different set of properties at the same location. Are they perceived as a single object undergoing change, or as two separate objects? Or how does the visual system deal with temporary occlusion of moving objects? Perceiving, or not perceiving, a single object across temporally or spatially separated stimuli is the temporal correspondence problem, sometimes referred to just as the correspondence problem or the motion correspondence problem, which is a specific version of the problem for visual perception of object motion.

Cutting a long and complex story very short, in vision, there is evidence that temporal object correspondence is determined by several factors, including spatiotemporal continuity (Hein & Cavanagh, 2012; Kolers, 1972; Kolers & Pomerantz, 1971; Navon, 1976; Ullman, 1979), continuity of object feature information (Caplovitz, Shapiro, & Stroud, 2011; Enns, Lleras, & Moore, 2010; Moore, Stephens, & Hein, 2010; Hein & Cavanagh, 2012; Hein &

Moore, 2012; Hollingsworth & Franconeri, 2009), and visual context (specifically a context that could be interpreted as partly occluding an object; Hein & Moore, 2014). Hein and Moore (2012) proposed that "the ultimate solution to the correspondence problem is given by a flexible weighting of all the variables available, without any special status given to spatiotemporal variables" (p. 985). Flexibility of weighting can explain why featural continuity information appears to carry more weight in some circumstances than in others. Thus, spatiotemporal information carries high weight for object correspondence when it is continuous, but featural continuity information carries more weight if the spatiotemporal information is disrupted (e.g. by occlusion) or unreliable. Other authors have made similar arguments (Caplovitz et al., 2011; Feldman and Tremoulet, 2006). There is also evidence for temporal object continuity perception in audition (Bregman, 1990; Hall, Pastore, Acker, & Huang, 2000; Litovsky, Colburn, Yost, & Guzman, 1999 Sanders, Joh, Keen, & Freyman, 2008; Wallach, Newman, & Rosenzweig, 1949), including continuity perceived across a temporal gap filled by the auditory equivalent of an occluder (Miller & Licklider, 1950; Riecke, van Opstal, & Formisano, 2008; Warren, 1999), and in the tactile modality (Kitagawa, Igarashi, & Kashino, 2009).

If continuity and object correspondence can be established at the level of perceptual objects or features, could that provide enough of a scaffold for perceived happening? It could be argued that, since vector information is bound to features and whole perceptual objects, it is automatically connected across time to the extent that the features and objects to which it is attached are connected across time. That would permit vector information to be bound across discontinuities such as the discontinuous sound stimulus in auditory continuity illusion research (Riecke et al., 2008). Under that hypothesis, connectives would not be necessary. To reiterate, the different times in this representation must be there at one time, as in Fig. 1(b), because of the no-history problem. The hypothesis would be that temporal object correspondence is established first, and then perceived happening is imposed on the identified temporal objects.

The hypothesis fails, however. The problem is that, while the cues of spatio-temporal continuity and feature continuity may be important to perception of correspondence in specific perceptual objects, the research does not explain how spatio-temporal continuity and feature continuity over time are perceived in the first place. That is what the ICOH does. The no-history problem applies. To generate continuity information of any kind, information about a perceptual object or feature must be retained on a short time scale, with both temporal differentiation and connection across the retained historical information. That is to say, at one moment, the course of recent history (to the extent that information about it is retained) must be represented in a way that reflects the temporal order of things. Therefore, perceived happening is not dependent on the continuity cues that serve to establish temporal object correspondence. On the contrary, the continuity cues depend on perceived happening: perceived happening makes possible the inference of spatiotemporal and featural continuity, which in turn determine temporal object correspondence.

7.3 State-dependent networks as a possible substrate of temporal distance and ordinality information in the ICOH

The semantic information about time in relation to happening, distance timing and ordinal temporal relations, must be supplied by some kind of timing mechanism. Thus, in the example of two brief flashes of light separated by a brief temporal interval, one or more timing mechanisms would be needed to support informational specification of the temporal order of the two flashes, the duration of each and of the gap between them, their time of occurrence, represented as increasingly far back in the past through successive moments of the ICOH, and of the whole sequence of events as a connected temporal sequence of perceptual information, to the extent that it occurs within the temporal boundaries of the ICOH.

Many possible timing mechanisms have been proposed and a thorough review of the applicability of those in the present context is not possible in the available space. At present the most plausible candidates are a general class of models proposing that time-dependent changes in neural circuits can encode both ordinal and duration information. The example that will be taken here is that of state-dependent networks (SDNs; Buonomano, 2000; Buonomano, Bramen, & Khodadadifar, 2009; Goel & Buonomano, 2014; Gorea, 2011; Grondin, 2010; Hardy & Buonomano, 2016; Mauk & Buonomano, 2004; Mauk & Donegan, 1997; Wittmann, 2013). The brief account here is based mainly on models proposed by Buonomano and Merzenich (1995) and Karmarkar and Buonomano (2007). However, any neurophysiological instantiation that satisfies the key functional principles would be compatible with the hypothesized properties of the ICOH.

In a SDN, when a stimulus arrives there is an initial brief spike response from one or more neurons, followed by a more gradual change in inhibitory post-synaptic potential (IPSP). The state of the IPSP modifies the response of neurons in the network to the next stimulus, with some cells inhibited and some cells facilitated, and the degree of modification depends on the state of the IPSP at the time of the next stimulus. Because of that, the response to the second stimulus potentially yields information about the amount of time that has passed since the first stimulus. That is a brief non-technical summary of the pertinent characteristics of the model proposed by Buonomano and Merzenich (1995). Buonomano and Merzenich focussed mainly on the possibility that their model can function as an interval timing mechanism, but they argued that it can also function as a register of ordinality: that is, such a mechanism can register one stimulus as occurring after another, as well as the temporal interval between them. As the authors commented, "if stimulus "A" is presented to an animal, "A" will produce a change in cortical network states as a result of time-dependent neuronal properties and stimulus "B" will then produce a pattern of activity that codes for "B" preceded by "A," rather than simple "B"" (p. 1030).

Karmarkar and Buonomano (2007) further developed the model, in part by adding a layer of output neurons that read out the encoded temporal information. More detail on how the output neurons work can be found in Karmarkar and Buonomano (2007), Buonomano and Maass (2009), and Haeusler and Maass (2007). In brief, output neurons receive connections from a large set of neurons in the SDN, and, in effect, the output neurons transform a temporal pattern of activity into contemporaneous timing information about the sequence of events which is then available to other processors. That is a critical addition for the present account, because it means that the time-dependent behaviour of the network generates information about temporal ordinality and intervals which can then, in principle, be read off as semantic information, transferred to other locations and stored for short periods of time. As Karmarkar and Buonomano (2007) said, "the network implements a temporal-to-spatial transformation" (p. 428); this means that temporal relations are informationally contemporaneously represented, in terms of the response distribution of neurons in the network. Thus, the temporal co-ordinate system in the ICOH could be constructed from the output of interval and ordinality information generated by SDNs.

Goel and Buonomano (2014) argued that SDNs are both local and intrinsic timing mechanisms, meaning that the properties relevant for temporal ordinality and timing information are manifested in almost all synapses and networks in the brain (e.g. Zucker, 1989; Zucker & Regehr, 2002). This is important because the ICOH encompasses a wide range of information processing, including most if not all sensory modalities, so the mechanisms that confer temporal ordinality and timing information on the information in the ICOH must be widespread in the brain. It also means that SDNs can underpin the informational representation, not just of particular things happening, but of the general sense of things going on in the world, located in a temporal framework.

The model developed by Buonomano and Merzenich (1997) was capable of discriminating intervals differing by 50 ms. Other papers have developed SDN models that can identify ordinal relations beween stimuli less than 50 ms apart (Goudar & Buonomano, 2014; Naud, Houtman, Rose, & Longtin, 2015). In principle, therefore, SDNs could support reasonably fine temporal discrimination in the ICOH. Even if a single SDN has a coarse temporal resolution, finer temporal resolution in perception could be accomplished by co-ordinated behaviour of multiple SDNs. Co-ordinated neural systems can support temporal discrimination on a scale of nanoseconds, albeit in bats rather than humans (Carr, 1993; Simmons, 1973, 1979), so the coarseness of a single system is not a bar to much finer discrimination in multiple co-ordinated systems.

The modelling work has been backed up with supportive research evidence (Buonomano, Hickmott, & Merzenich, 1997; Buonomano & Maass, 2009). There is evidence from more than one modality, including vision (Nikolić, Häusler, Singer, & Maass, 2009), audition (Goudar & Buonomano, 2014; Haeusler & Maass, 2007; Karmarkar & Buonomano, 2007; Klampfl, David, Yin, Shamma, & Maass, 2012; Naud et al., 2015), whisker movement in mice (Pitas, Albarracín, Molano-Mazón, & Maravall, 2017) and olfaction (Mazor & Laurent, 2005), which is important to the claim that SDNs can support timing information in perceived happening throughout perception. Other evidence for neurally embodied timing mechanisms with properties consistent with SDNs has also been reported (Haeusler & Maass, 2007; Klampfl et al., 2012; Nikolić et al., 2009).

The proposal, then, is that there is a network of SDNs (or multiple networks) that is involved in setting the temporal co-ordinates of the ICOH. There is essentially a three-stage process. Stage 1 is the activity of the SDN network. This spontaneous activity generates the IPSPs that modify the state of the network and therefore the next firing. In the second stage, the difference in activation dependent on the state of the network can be read off and transformed into information about temporal ordinality and timing. That in turn is transferred to a sub-second time scale store where it is connected to similar information already there: that is the third stage, where the temporal information sets the framework and co-ordinate system of the ICOH.

This is no more than a rough sketch of general principles, but it perhaps suffices to show how the ICOH could be instantiated in a neurophysiologically plausible way. It would be premature to rule out mechanisms other than SDNs as possible substrates for timing information in perceived happening. It is possible to specify some requirements that an alternative hypothesis must satisfy. These include widespread occurrence in the brain, capacity to generate information about temporal ordinality and interval timing, the possibility of output from them feeding into high level perceptual processing, capacity to account for all kinds of perceived happening in all modalities where it occurs, including the mere persistence of static objects, and fine temporal resolution. SDNs meet all these requirements, but it is not yet clear whether any other timing mechanism does.

7.4 What evidence is there?

It could be argued that the present proposal is premature inasmuch as there is little evidence for it. There are two replies to that. One is that the problem addressed in this paper is important and neglected, and a theoretical proposal can serve as a stimulus to research by many people over and above the author of it. The other reply is that there is evidence that is consistent with what is being proposed.

One kind is the evidence discussed earlier for representation of object motion information in informational sensory memory, which is on the time scale proposed for perceived happening (Narasimhan et al., 2009; Shooner et al., 2010; Tripathy & Öğmen, 2018). Another kind is evidence that neural responses to a stimulus differ depending on what the previous stimulus was (Klampfl et al., 2012; Nikolić, Häusler, Singer, & Maass, 2009; Nortmann, Rekauzke, Onat, König, & Jancke, 2015). This shows registration of ordinality and change on a short time scale and could support a mechanism for constructing a series of ordinal representations.

The ICOH is a spatiotemporal map of information in perception and sensory memory. Evidence for just such a map has been found in several studies (Galletti & Fattori, 2003; Huynh, Tripathy, Bedell, & Öğmen, 2017; Melcher & Morrone, 2015; Yoshimoto, Uchida-Ota, & Takeuchi, 2014; Zimmermann et al., 2014). In the case of space, the map is laid out in spatiotopic (as opposed to retinotopic) co-ordinates (Yoshimoto et al., 2014) and perceptual objects are located in that space. In their review, Zimmermann et al. (2014) emphasized that the map encompasses temporal as well as spatial information.

Much more evidence is needed, of course, particularly tests of the specific proposed properties of the ICOH, but there is sufficient evidence to show that the ICOH can be fitted into a coherent overall account of perception and informational sensory memory.

8. Conclusion

The no-history problem is real. Everything in perception is subject to it. Yet the no-history problem and the ways in which the brain may deal with it have been almost entirely neglected in psychology and neuroscience. For any perception of things happening or persisting over time to occur, the brain must construct a representation of information about recent history that exists as an integrated whole at a single moment. That set of information must have properties that account for perceived happening. The ICOH is proposed as an information structure that has that function. Even if the ICOH proposed here is not correct, there must be some way of dealing with the no-history problem, such as to generate the perception of happening that we actually have, and that way must involve some form of contemporaneous representation of historical information on a short time scale. This, I would argue, is a problem of fundamental importance in psychology and neuroscience.

Footnotes

1. This is rather a stretch for perception of a stationary object merely persisting in time, since it could be argued that nothing is actually happening, but there does not seem to be any simple word that covers all that is included here, so I hope readers will accept this use of the term for the purposes of this paper; cf. Gruber and Block (2013, p. 92).

2. This is a contentious proposition. Some philosophers and physicists have argued that the universe is a four-dimensional space-time manifold, and that no moment in the temporal dimension is privileged over any other: neither a present moment nor a flow of time are mandated by the known laws of physics (Al-Khalili, 2012; Barbour, 1999; Buonomano 2017; Dainton, 2008, 2014; Davies, 1995; Greene, 2004; Gruber & Block, 2013; Smart, 1980). Others have argued that there is a present moment, that the present moment is all that exists, and that there is some sort of flow of existence through successive temporal co-ordinates (Arstila & Lloyd, 2014; Buonomano, 2017; Dainton, 2008; Dorato & Wittmann, 2015; Zimmermann, 2011). That position is generally known as presentism. It is not the purpose of this paper to take any view on whether presentism is correct or not. However, the assumption of presentism is implicit in and necessary to any scientific description or account of anything that happens. The implicit assumption of a present moment and the flow of time is there in accounts of neural transmission, nuclear reactions, the demise of the dinosaurs, and intercepting a moving object with a racquet. Without that assumption, accounts of that sort can make no sense. The assumption of presentism will be adopted explicitly here, as it is implicitly in much other work in psychology and neuroscience, in order to work through its implications for perception. If it is wrong here, it is wrong everywhere in science.

3. I came across Dainton (2008) after I had been working on the ICOH proposal for about five years, and the ideas presented here owe nothing to those in Dainton's paper. There has been some acknowledgement and analysis of the no-history problem in philosophy (Dainton, 2008, 2014; Herzog, Drissi-Daoudi, & Doerig, 2020; Rovelli, 2018), but philosophical hypotheses are tested not by research evidence but by criteria such as logical possibility and intelligibility. For example, Dainton (2008) argued that the hypothesis of contemporaneous representation of the recent past runs the risk of an infinite number of moments being included in the representation which would, if correct, mean that the hypothesis failed on grounds of logical impossibility. This would not be a problem for any scientific hypothesis because the granularity of the representation would be set empirically by evidence about the operating characteristics of the brain, such as the fact that the action potential for a typical neuron lasts about 1 ms (Goldstein, 2014).

4. I originally wanted to call the information structure the "temporal map". However that term has already been used to refer to a representation of a temporal distribution of events on a time scale of several seconds (Balsam & Gallistel, 2008), so the current, more descriptive term is used to avoid possible confusion.

5. In physics, vectors can be subject to arithmetical operations such as multiplication. In the present application there could be processes functionally equivalent to arithmetic that integrate vector information over time to obtain a summary of change over that period, but the possibility of such processes lies outside the scope of this paper. The representation of the history of change over a recent period of time is the present concern, not the compilation of the entries in that record into a summary.

6. Nothing written here is meant to imply that semantic information in sensory memory cannot be lost or obscured. Bhardwaj et al. (2012) have shown that semantic information can be

rendered unavailable by a semantic mask with similar features to those of the target. The record of the past in the ICOH should be understood as imperfect and incomplete.

Acknowledgements

I am grateful to Marc Bühner, Michael Herzog, Rob Honey, and Mark Johansen for helpful comments on earlier drafts of this paper.

Declaration of conflict of interest and financial disclosure

The author has no conflicts to disclose.

Data availability

This is a theoretical paper an dthere are no associated data.

Funding statement

There was no fiunding for this paper.

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