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Conscious Perception: Discreteness vs. Continuity

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Abstract: **Introduction**. Is perception discrete or continuous? This question has a long history, but in the light of experimental data obtained in recent years, it is gaining relevance again. The available models rely on different understandings of discreteness, and they highlight different units of discrete perception. **Theoretical justification**. This article reviews the development of discrete models of perception and discusses the various theoretical evidence for discreteness of perception. **Results and discussion**. The article provides a review of experimental studies supporting discrete models and their general critique. The results of the latest studies support the idea that it is precisely conscious perception that is discrete, while unconscious information processing can be continuous or carried out with higher temporal resolution. The authors compare two popular contemporary approaches to discrete perception. One approach assumes that the discrete unit of perception is relatively small and related to temporal resolution, but that it is not universal - discretization can occur at different frequencies, for example, for different modalities. The second approach associate's discretization with the need to calculate the most meaningful interpretation of incoming data. The discrete unit in this approach (the time window of unconscious processing) is universal, but its duration is not fixed and depends on the nature of incoming data. Authors also propose an alternative approach based on V. M. Allakhverdov's negative choice theory, which implies the existence of the unconscious processing window, the duration of which is not constant. This approach suggests a novel idea that the duration of the window depends on the complexity of control operations, the goal of which is to select information for conscious processing. Authors discuss the capabilities of this approach to explain the temporal dynamics of priming and the attentional blink effects where the difference in the duration of discrete window can be seen as the manifestation of the general logic of discretization.

Keywords: discrete perception, visual perception, perceptual moment, postdictive effects, integration window, consciousness, negative choice, priming effects, negative priming, EEG oscillations

Highlights:

- Recent data indicate that the duration of a discrete unit of conscious perception can be up to several hundred milliseconds.

➢ Discretization at the level of unconscious processing has higher frequency.
➢ According to the approach we develop, discretization at the level of conscious perception appears because of the need to control the prepared representation for them to become conscious.
➢ The complexity of the control operations performed before awareness affects the duration of the unconscious processing window.
➢ Тамhe idea that the duration of the «window» depends on the complexity of control operations has the potential to explain the temporal dynamics in a number of experimental effects, such as the masked priming effect or the attention blink effect.

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Introduction

When we perceive something consciously (e.g., movement), how does the content of our consciousness change over time? Is it updated continuously or discretely (at certain moments)?

The problem of temporal organization of perception has been on researchers' minds since antiquity (see Zeno's Arrow paradox) till the present day. However, over time and with the change of paradigms scientists focused on different issues of the problem. Dainton (2018) formulates the basic version, which has occupied philosophers for centuries, in this way: it seems that we can be directly aware of only what is in the present and, therefore, our awareness must lack temporal depth. But how, then, can we directly perceive changes in objects? Some of the possible answers suggest that, despite the subjective experience of perception as a continuous flow, the process requires some discreteness.

In cognitive psychology due to emergence of the recent experimental data in support of discrete models the issue of perceptual discreteness has become a hot topic once again (e.g., Herzog et al., 2016; White, 2018; Fekete et al., 2018; Doerig et al., 2019). In this article we will attempt to justify the logical necessity of discretizing the perceptual process and review the main theoretical and empirical arguments in favor of discrete models. We will also look at the criticisms of the available models of discrete perception and propose a possible mechanism of discrete perception, which we believe takes into account the shortcomings of other models.

Let's begin with understanding what is meant by discreteness and continuity. The question of perceptual discreteness in a general sense is whether perceptual images arise continuously or at particular moments in time (Doerig et al., 2019). Miller (1988) notes that when we talk about information processing by a cognitive system, a strict mathematical definition of discreteness and continuity inaccurately describes their distinction, so it is more appropriate to separate these processes based on the size of the discrete units rather than on the very fact of their existence. It is possible to regard some process as continuous, even if at the level of its neural mechanism it is discrete in the strictest sense, i.e. the discretization unit is extremely small. Thus, the fact that perception is based on discrete (impulsive) brain activity is not enough to define perception itself as a discrete process.

Understanding what exactly a discrete unit is when we talk about conscious perception varies depending on the approach. Dainton (2018) identifies three main groups of philosophical theories on the temporal organization of perception: Cinematic Models, Retentional Models and Extensional Models. Cinematic models assume that the 'stream of consciousness' consists of a continuous sequence of static ‘snapshots’. In Retentional Models units are ‘episodes’, which lack temporal extension, but involve integration of new incoming data with the previous data, thus, representing the time changes in objects’ properties. As noted by Herzog et al. (2020), temporal characteristics of objects within these models are encoded in a non-temporal format, similarly to other features such as shape or color. A third group of models – Extensional Models – argues that episodes of consciousness are themselves extended in time, so time changes can be represented directly. Considering both philosophical and psychological models, Herzog et al. (2020) add a discreteness parameter to this classification, noting that all three types of models can assume both discreteness and continuity of perception.

The discrete cinematic approach assumes that perception is discrete if the evaluation of two events as sequential or simultaneous depends not only on the temporal interval between them, but also on the correlation of their presentation to some discrete neural process (VanRullen & Koch, 2003). In an alternative approach (Herzog et al., 2020) discreteness is not based on the sequential/simultaneous perception, but on how the data integration occurs prior to emergence of perceptual image: within a discrete time window (discrete retentional models) or continuously, within a sliding time window (continuous retentional models) (Herzog et al., 2020).

Theoretical justification

Development of the idea of discrete perception

We start with looking at factors that led to the popularity of discrete models in the first half of the 20th century. The development of discrete models is discussed: from the classical Stroud (1967) model to modern approaches that recognize the possibility of simultaneous discrete sampling with different frequencies (VanRullen & Koch, 2003; VanRullen, 2016). The paragraph concludes with the two-stage model of M. Herzog and colleagues (Herzog et al., 2016; Herzog et al., 2020), which combines the strengths of both discrete and continuous models.

The idea of discrete perception has gained and lost popularity several times during its existence. After the philosopher C. E. Baer explicitly proposed the idea in the nineteenth century (VanRullen, 2018), it soon received first experimental confirmations. For example, experiments showed that people perceive two stimuli presented consecutively at the same position as one if the time interval between them is less than a certain threshold, and as two if the interval exceeds the threshold (in Sokoliuk & VanRullen, 2019) (later it was also explained without the discreteness assumption, see section «A Critique and Defense of Discrete Models,» - *author's note*). Similarly, the phi-phenomenon was demonstrated (in Schultz, Schultz, 2002). The idea of discrete perception became widespread in the early 20th century (see VanRullen, 2018; White, 1963), facilitated by the appearance of the cinematograph (which became a metaphor for the perceptual process), and the discovery of alpha rhythm (which scientists immediately tried to link to the cyclic processes that go with perception (see Harter, 1967)).

The spread of computer metaphor has also contributed to the popularity of discrete models. For example, J. M. Stroud, author of one of the influential models of discrete perception, suggests that the human brain, like a computer, «solve logical problems by a finite number of steps in a limited time», which defines the necessity discreteness of information processing (Stroud, 1967, p. 625). Psychological time, according to the model proposed by Stroud, is discrete and consists of perceptual moments, each of which is equal to approximately one hundred milliseconds (however, he believes that this value may vary within the range of 50-200 ms). Within one such moment all information about temporal parameters, such as duration and order of appearance of stimuli, is lost. If from the point of view of physical time such a «moment» has a certain duration, from the point of view of psychological time it is the minimal unit devoid of any temporal length. Using classification proposed above, this model represents discrete cinematic models.

J. M. Stroud relates the duration of the perceptual moment to the perception of motion. It is assumed that motion in a film is perceived as motion if at least one frame of the film is presented at one such «moment». This distinguishes the J. M. Stroud's model from modern cinematic models, where it is assumed that motion can be represented within a single «moment», despite its static nature, because at the neural level any motion is encoded (similarly to the features of static objects) as the firing rate of the corresponding detector neuron (Crick & Koch, 2003).

A similar concept to J. M. Stroud's model of discrete units of perception universal for all modalities was proposed by Pöppel (1997, 2009). The duration of such units is 30-40 ms, and it is assumed that within its frame all events are perceived as simultaneous. Processing information with higher temporal resolution is possible (when, for example, one needs to localize sound in space), but for events to be perceived as sequential, they must be part of two separate units. One current approach, developing the ideas proposed in early discrete cinematic models, also links discretization to the temporal resolution of perception and states that all temporal information is lost within a single perceptual moment (e.g., VanRullen & Koch, 2003; VanRullen, 2016; Schneider, 2018; Ronconi et al., 2018). Following J. M. Stroud, VanRullen and Koch (2003) suggest that the duration of perceptual moment (i.e., the frequency with which the brain mechanism responsible for discrete perception operates) varies depending on the perceptual characteristics of the stimulus, observer's attention and the characteristics of the task. However, an important difference from the earlier models is the rejection of the idea that the perceptual moment, even if it has flexible duration, is a universal unit of perception. They argue that discrete sampling can happen simultaneously with different frequencies (e.g., for different modalities or for different perceptual features) (VanRullen & Koch, 2003; VanRullen, 2016).

In recent years researchers obtained a lot of new evidence of discrete perception, which allows to clarify previously proposed and criticized models. One of the modern approaches developing the idea of discrete perception, which claims to resolve the contradictions of the previous theories, was proposed by M. Herzog and colleagues (Herzog et al., 2016; Herzog et al., 2020). In this approach discreteness of perception is associated with the need to integrate information over time and, most importantly (since integration itself can also be carried out continuously) – with the construction of a meaningful interpretation of the gathered data (and this is necessarily a discrete process).

They proposed that discrete awareness is preceded by a period of unconscious processing, the duration of which may vary depending on the characteristics of the incoming information. Moreover, most of this time is required not for feature detection, but for identifying the best interpretation.

Using the classification, we provided in the previous paragraph, the model of M. Herzog and colleagues refers to discrete retentional models. In this approach the size of the unconscious processing window is not directly related to temporal resolution - although the content of consciousness is discretely updated, temporal parameters (such as duration or sequence of stimuli presentation) are not lost as in cinematic models but are encoded in a non-temporary form similarly to attributes like color or shape. As the authors write: «...40-ms stimulus is not continuously perceived during the 40 ms when it is presented. <...> Rather, the duration is encoded as, for example, the output of a duration detector» (Herzog et al., 2020, p. 833). In this case, all properties enter the consciousness simultaneously as part of a single coherent image of perception regardless of how their analysis took place.

Experimental data of M. Herzog and colleagues show that the duration of a discrete processing window can reach 450 ms, i.e., awareness can occur with approximately such a delay. The proposed model does not impose any logical limits on the possible duration of such windows. The authors note, however, that longer windows may be required in situations where incoming data have multiple meanings or a lot of noise. They argue that a typical window duration of 300-400 ms may be optimal: long enough to compute a single-meaning interpretation, but small enough to allow a timely response to the received data. At the same time the authors note that simple automatic reactions can take place even before full processing and comprehension are complete and conscious percept is formed.

What is the purpose of discretization?

This paragraph reviews various theoretical justifications for discrete perception, such as the presupposition of a greater efficiency of discrete processing (VanRullen & Dubois, 2011; Chota & VanRullen, 2019); reduced uncertainty associated with different speed of processing different types of information (Pöppel, 2009), the need to build meaningful and unambiguous interpretation of incoming data (M. Herzog and colleagues, B. J. Baars, V. M. Allakhverdov) and verification of the chosen interpretation before awareness (V. M. Allakhverdov).

Starting with the same question of whether conscious perception is continuous or composed of discrete units, authors from different approaches theorize differently in favor of discreteness (e.g., VanRullen & Koch, 2003; Chakravarthi & VanRullen, 2012; Herzog et al., 2020).

In the approach developed in early cognitive psychology, discretization was justified by the assumption of the logical nature of information processing in the brain (Stroud, 1967). The argument in favor of discrete algorithms was their potentially greater efficiency (Harter, 1967; Shallice, 1964).

The authors of one of the current approaches (VanRullen & Dubois, 2011; Chota & VanRullen, 2019) also appeal to the higher efficiency of discrete processing: instead of processing incoming data continuously, the visual system divides it at a certain frequency, testing the environment for changes. The continuous stream is broken down into discrete portions, which then are processed further.

A different approach is suggested by Pöppel (2009), arguing the need for discretization in terms of the temporal perception issues. E. Pöppel points out the problem: the speed of information transferring and processing differs for different modalities and different types of information within one modality. For example, auditory and visual information reaches the central structures in the brain at different rates. So, E. Pöppel suggests that to minimize uncertainty the brain uses neural oscillations – all data received within one period unites into one block and treated as simultaneous (i.e. one period of oscillations sets one «perceptual moment», - *author's note*).

When talking about efficiency, different authors generally do not explicitly distinguish between unconscious processing and the process of updating conscious information. At the same time, considerable evidence suggests that information can be processed with higher temporal resolution at the unconscious level than at the conscious level (see Elliott & Giersch, 2016), but the rationale in terms of computational efficiency or uncertainty reduction does not explain why an additional reduction in resolution occurs when moving from unconscious to conscious processing.

Another alternative hypothesis is proposed by Chota (2020): discretization of information may be important for executing predictive coding algorithms, allowing comparison of incoming data with the predicted one.

Within the approach developed by M. Herzog and colleagues (Herzog et al., 2016; Herzog et al., 2020), discretization at the level of conscious perception is associated with the need to construct a meaningful and unambiguous interpretation of incoming data, which is impossible if the incorporation of new information and changes in conscious contents occurs continuously (see «Critique and defense of discrete models»). Similar ideas are also expressed by Elliott & Giersch (2016). The proposed approach is consistent with the inferences of other authors who arrive at the necessity of discrete processing of information, because it is necessary to verify the results of processing for their further use. For example, Baars (1988) gives the following example: if we consider A + B = C, and C + D = E, then we cannot perform the second action without having performed the first action in the previous step and without verifying the correctness of the task. V.M. Allakhverdov (2021) expresses a similar idea. He suggests that before information gets into consciousness, we need to check the unconsciously prepared representations for coherence and inconsistency. Such verification is impossible if representations were constantly changing by the new data.

Thus, it is theoretically possible to assume that perception should be discrete, but it is necessary to understand the execution of the process in much more detail. For this purpose, let us consider some of the main directions of research that have contributed to the development of the idea of discrete perception.

Results and discussion

Recently, researchers have provided more and more data supporting discrete models of perception. It is possible to distinguish several directions of research.

Studies of perceptual rhythms caused by EEG oscillations

This section presents experimental evidence for a correlation between EEG oscillations and cyclic changes in perception. Hypotheses suggesting a relation between EEG rhythms and the mechanisms providing discrete perception are considered.

EEG oscillations are often attributed to the functioning of the neural mechanism underlying discrete perception (e.g., Valera et al., 1981; VanRullen, 2016). When researchers discovered alpha rhythm first hypotheses relating to discrete perception were almost immediately to follow. Thus, W. Pitts and W. S McCulloch in 1947 proposed the idea of «cortical scanning» (cyclic sequential activation of cortical areas) underlying the algorithm for shape recognition and linked this process to the alpha rhythm (in this model such cyclic sequential activation is added to the activation caused by specific afferents, allowing the latter to cross the threshold. N. Winner, who developed a similar model, compared this process with the process of image processing in a television set based on a telescope (according to Harter, 1967), - *author's note*). Expanding on this idea, J. M. Stroud designated one time period of the scanning as one discrete «moment» (according to Harter, 1967). An alternative hypothesis, which appeared at the same time, suggested that alpha oscillations reflect cyclic changes of cortical excitability (Lindsley, 1952), which may also influence perception, including structuring it in time (Harter, 1967). This idea, in contrast to the «scanning» concept, is still relevant today (e.g., Mathewson et al., 2009; Milton & Pleydell-Pearce, 2016).

There has been exceeding evidence of a connection between brain rhythms and cyclic changes in the process of perception. The phase of EEG oscillations before the appearance of stimuli correlates with the specifics of reaction to the stimuli in a variety of perception and attention tasks. Moreover, this relationship has been observed most frequently for alpha and theta frequency ranges (Alpha rhythm has been associated with discrete sampling in sensory processing, and theta rhythm with attentional sampling (VanRullen, 2016), - *author's note*) (see reviews: VanRullen et al., 2011; VanRullen, 2018; Haegens & Golumbic, 2018). Researchers demonstrated this relation for reaction speed (e.g., Callaway & Yeager, 1960; Drewes & VanRullen, 2011), for the probability of identification near-threshold and masked stimuli (Busch et al., 2009; Mathewson et al., 2009; Busch & VanRullen, 2010; Fiebelkorn et al., 2013; Zhou et al, 2021) and the likelihood of seeing the TMS-induced phosphene (Fakche et al., 2022), for performance in visual search tasks (Dugué et al., 2015), for the extent to which stimulus perception is determined by previously formed expectations (Sherman et al., 2016), etc. In addition, there are many studies demonstrating rhythmic fluctuations in behavioral measures such as stimulus recognition accuracy and reaction time (e.g., Dehaene, 1993; reviewed by VanRullen, 2018).

Do these data confirm the existence of discrete perceptual units? Periodic changes in the accuracy of recognition of a briefly presented stimulus may indicate that when it appears in a certain phase of the period, it falls between two perceptual moments and is therefore not perceived (VanRullen, 2018). However, there is an alternative explanation: perception is not discrete, but only subject to rhythmic modulations, which are related, for example, to changes in neuronal excitability (VanRullen, 2016; Harter, 1967). R. VanRullen suggests that to prove discreteness of perception the observed changes must concern not only the quality of perception, but also its temporal structure. And such data has been obtained (although not that much yet). For example, if two objects come into contact and then the second object starts moving, the assessment of causality between these events is related not only to the temporal interval between them, but also to the phase of the alpha rhythm before the contact (Cravo et al., 2015). It has also been found that when the interval between two stimuli is equal, the pre-stimulus phase of the alpha rhythm correlates with perceiving them as presented simultaneously or sequentially (Valera et al., 1981; Milton & Pleydell-Pearce, 2016). Moreover, the frequency of the alpha rhythm correlates with the temporal resolution of visual perception (Samaha & Postle, 2015). When participants' alpha rhythm was entrained with 10 Hz TMS stimulation, their ability to estimate the order of two rapidly presented, consecutive stimuli varied depending on whether they appeared within the same artificial time window (between two TMS pulses) or different ones (Chota et al., 2021).

As mentioned above, one possible evidence of discretization focuses on predictive processing: the need to compare predictions and incoming data (Chota, 2020). According to one of the hypotheses, the alpha rhythm may be a marker of this kind of processing (Alamia & VanRullen, 2019). Alamia & VanRullen (2019) used a simple model that implements a predictive coding algorithm (in such models, neurons at each level predict the result to be obtained at the previous level, the prediction is sent down, and the prediction error value returns to the top) and used it to reproduce a number of features of alpha oscillations. One such feature is the so-called «perceptual echoes» of the incoming signal (VanRullen & Macdonald, 2012). When participants look at a stimulus whose brightness changes randomly, the correlation was found between the brightness values and the EEG responses. As the temporal shift between the stimulus brightness and the EEG signal increases, this correlation changes with a frequency equal to that of the alpha rhythm, and these fluctuations gradually subside over 600-1000 ms (moreover, the frequency and amplitude of the «perceptual echo» in a particular subject correlated with the frequency and amplitude of the alpha rhythm observed at rest with eyes closed - *author's note*). Alamia & VanRullen (2019) provided data corresponding to randomly varying luminance to the model input, while the second (upper) level output was treated as analogous to the EEG signal. When the delays between levels added to the model roughly matched the real biological system, the cross-correlation function between the data and the model EEG signal showed similar oscillations in the alpha range. Using a more complex model with a larger number of levels researchers reproduced another feature of the alpha oscillations – their propagation in the form of travelling waves. The model produced forward travelling waves (in the direction from the lower to the upper layers) during sensory data processing and backward travelling waves when top-down predictions were sent and there were no input data. Similar waves were found in the actual EEG signal: forward waves when subjects looked at the sensory stimulus, and backward waves when the eyes were closed (another study (Luo et al., 2021) showed a relationship between «perceptual echo» and conscious perception. Participants looked at two stimuli under binocular rivalry, with the brightness of each stimulus changing independently at random. The cross-correlation with the EEG response was calculated separately for each of them. The alpha oscillation power of the «perceptual echo» was higher for the stimulus that was currently conscious. At the same time, the propagation of the «perceptual echoes» as a travelling wave from the posterior to the frontal regions took place independently of awareness, - *author's note*).

The data that we discuss in more detail in the paragraph «Studies of long-lasting postdictive effects» shows that unconscious integration of information can last up to several hundred milliseconds, which makes the idea that perceptual content (if we recognize it as discrete) can be updated with the frequency of alpha or theta rhythms unlikely. Therefore, we assume that the evidence given in this paragraph relates rather to the unconscious stages of processing. This is also supported by the inability to identify one universal sampling frequency (see paragraph «Criticism and defense of discrete models»).

We think it is important to specify that variability of duration of the discrete window at the physiological level, observed in the presented experiments, does not condition the necessity of the same temporal window at the consciousness level, because this window is defined not by the limited resolution that brain processes can provide, but by the logic of information processing and verification for solving the existing tasks. We assume that several discrete elements of information processed at the physiological level can appear in one window at the psychological level. Therefore, it is necessary to consider other phenomena, in which one can observe discreteness of conscious perception, and to suggest possible logical mechanisms for choosing the duration of discretization.

Studies of behavioral evidence of discrete perception

This paragraph considers phenomena directly or indirectly confirming the discrete approach: studies of sequential or simultaneous perception of motion and its causes, some visual illusions (flickering wheel illusion, wagon wheel illusion). We also look at postdictive effects (the influence of subsequent stimuli on the perception of previous stimuli), which assume that information is integrated before awareness.

Many early studies limited themself to identification of a temporal window in which all stimuli are perceived as presented simultaneously or, for example, several successive flashes merge in perception into one (see White, 1963; VanRullen & Koch, 2003). The temporal parameters of causal perception have also been investigated, under conditions in which a moving object touches another object, after which that object also begins to move (Shallice, 1964). It was found that with a delay lesser than a certain threshold (up to 56 ms), subjects felt that the first object directly triggered the movement of the second object. When the interval is increased to 140 ms, the second object seems to «stick» to the first object and starts moving with a delay, and when the interval is increased even more, causality is no longer perceived (see White, 2018). T. Shallice suggested that causality is not perceived if the interval between contact and the start of movement of the second object includes two or more perceptual moments. If this interval includes only one moment, person can perceive both causality and delay («sticking» impression), if the interval is less than one moment then the person can only perceive causality (criticizing this explanation, White (2018) notes that if the perceptual moment is devoid of subjective duration (the version proposed by J. M. Stroud), then if the interval is one perceptual moment, there should be no perception of delay and «sticking.» Another problem noted by P. A. White is that in several studies the perception of causality is preserved at much longer delays, depending on the conditions of presentation, - *author's note*). Later it became clear that these effects could be explained without the assumption of the discreteness of the integration window.

Some visual illusions are associated with discrete perception, such as the flickering wheel illusion (perceived flickering of a circle consisting of alternating white and black segments of a certain spatial frequency and located at the visual periphery) (the frequency of illusory flickering corresponds to the alpha rhythm range (Sokoliuk & VanRullen, 2019), - *author’s note)* or the wagon wheel illusion when one perceives an illusory change in the direction of wheel’s motion (Sokoliuk & VanRullen, 2019). Such a change happened when participants were looking at a recording with a frame rate less than the rotation rate, but several studies have shown that it can also occur when observing the rotation «live» and when no external sources of sampling are present. The illusion was observed at different rotation frequencies but peaked at a frequency around 10 Hz. White (2018), however, believes that this illusion occurs too rarely (in 30% of samples) and at exceedingly large frequency range to be attributed to the presence of discrete perceptual «frames».

Also associated with perceptual discreteness is the existence of postdictive effects (e.g., review by Shimojo, 2014), when a stimulus presented later has an effect on the perception of stimuli presented earlier (Herzog et al., 2016; Schneider, 2018). Some of the best-known examples of such effects are the color phi-phenomenon (Kolers & von Grünau, 1976) and the backward masking effect (e.g., Breitmeyer & Ogmen, 2000). Other examples include the so-called «cutaneous rabbit» effect, a similar effect to the phi-phenomenon in the tactile dimension (Geldard & Sherrick, 1972), as well as illusory reordering of stimuli presented in sequence for a short time (with a delay of less than 50 ms the second stimulus is more often perceived as presented first, if its contrast is higher) (Bachmann et al., 2004).

Another widely studied phenomenon of this series is the flash lag effect (flash lag effect; Nijhawan, 1994) and its different versions. If one stimulus moves and the second flashes alongside it at some point for a short time, observers overestimate the position of the first stimulus: it seems that the second stimulus appears with a lag - later than it actually does. This effect persists even when the flash coincides with the beginning of the movement (i.e., both stimuli appear simultaneously), but is absent if the second stimulus flashes at the moment the first one stops moving (there are some evidence that the effect can also persist under these conditions, but only if one needs to estimate the absolute position of the moving stimulus at the end of its motion, rather than the position relative to a flashed object, as in most studies (Hogendoorn, 2020), - *author's note*), which does not allow to fully explain the effect by the extrapolation of motion alone. The generalized flash lag effect occurs when the first stimulus does not move but changes in some other aspects, such as color or spatial frequency (Sheth et al., 2000).

It was also shown that the magnitude of the flash lag effect correlates with the phase of the EEG oscillations (in the alpha and theta bands) around the moment of stimulus onset (Chakravarthi & VanRullen, 2012). Chota & VanRullen (2019) went further and entrained the oscillations using an annulus around the stimuli which luminance fluctuated at a frequency of 10 Hz. The size of the flash lag effect varied depending on which phase of the entrained cycle corresponding to the stimulus onset. This is consistent with the interpretation that the effect arises in the process of discrete sampling. If the discretization process only saves information on stimulus position at the end of a discrete time window, then the closer a static stimulus is presented to the end of that window, the more accurate the estimate of the position of the moving stimulus at the time of its presentation (Schneider, 2018).

Studies of long-lasting postdictive effects

The discussion of postdictive effects continues. While it is possible to explain the short-term postdictive effects discussed in the previous section with models involving discrete sampling at alpha and theta frequencies, the discovery of the long-lasting (up to 450 ms) postdictive effects indicates that conscious percepts may update less frequently than classical discrete models suggest.

The research of postdictative effects is important in estimating the size of a discrete unit of conscious perception (namely, it helps identify of its possible boundary values (Herzog et al., 2020)), as it demonstrates how long integration can take before any (possibly intermediate) outcome becomes conscious. As White (2017) points out, temporal integration of information can occur at intervals ranging from a few milliseconds to several seconds, depending on the type of information. For example, tactile stimuli that arrive at intervals of 1-2 ms are being integrated into a single tactile texture percept. Motion perception under visual noise involves temporal integration that could last for 2-3 seconds (Burr & Santoro, 2001). A recent study found that when perceiving a slowly changing visual stimulus, integration can take up to 15 seconds (Manassi & Whitney, 2022). However, this is not the integration required for stimulus awareness per se, as conscious perception cannot be delayed by fifteen seconds, or even three seconds.

However, recent studies have been demonstrating postdictive effects lasting up to several hundred milliseconds, the occurrence of which cannot be explained by discrete sampling at alpha and theta band frequencies (e.g. Thibault et al., 2016; Sun et al., 2017; Stiles et al., 2018; Drissi-Daoudi et al., 2019; Drissi-Daoudi et al., 2020; for review see Herzog et al., 2020). For example, a correct cue about the position of a faint stimulus presented at 50 ms to the right or left of the fixation point helps more accurately determine its orientation, even when presented 400 ms after the stimulus itself (Thibault et al., 2016).

In another study (Scharnowski et. al., 2009), transcranial magnetic stimulation (TMS) was used to manipulate which of the two stimuli would dominate after feature fusion. Although the presentation of the first and the second stimuli together took only 60 ms, the effect of TMS on their integration persisted even when the TMS pulse took place at 400 ms after the first stimulus onset. Similar results were obtained when visual masking was used instead of TMS (Pilz et al., 2013). The mask affected which stimulus would dominate the percept, even when presented 200 ms after the first stimulus onset. These data show why studying the temporal resolution of perception is not enough to determine its temporal structure (by looking only at the temporal resolution, one could see that with stimulus onset asynchrony (SOA) of 30 ms, integration occurs, and with SOA of 200–400 ms, stimuli are perceived separately, but these data would not show how long the integration takes, and with what delay the final percept is formed, – *author's note*).

Promising results have been obtained using the Sequential Metacontrast Paradigm (SQM; Otto et al., 2009). Under this paradigm, a central vertical line consisting of the two segments is presented, followed by a sequence of frames with pairs of parallel flanking segmented lines moving away from each other. Participants must keep their attention on one of the two diverging lines. The first central line stays unnoticed, as flanking ones mask it, but if it contains a left or right vernier offset, this affects the perception of the line to which attention is drawn from the two perceived diverging lines – it seems to have an offset in the same direction. If a flanking line on the one of the following frames also has a vernier offset, they are integrated: two offsets that are in the opposite directions cancel each other (neither of them is perceived, and the line seems to be straight); offsets that are in the same direction are summed (the resulting offset seems to be more pronounced). Integration takes place before conscious perception: participants cannot report the individual offsets, only on the resulting percept.

Using this paradigm, researchers were able to show (Drissi-Daoudi et al., 2019) that such integration can occur within discrete temporal windows lasting for up to 450 ms. The presence of integration depended not on the interval separating the stimuli itself, but on whether the stimuli fell into the same discrete window or into different ones (the authors prolonged the trial and added three vernier offsets instead of two; moreover, there was a longer time interval between the first and the second verniers than between the second and the third ones. Yet, it was the first and the second offsets that were integrated in perception (as they probably fell into the same temporal window), and the third was perceived independently. With further extension of the trial, it was shown that integration within the second temporal window happens in the same way as in the first one (Drissi-Daoudi et al., 2019), – *author's note*). A displacement of stimuli on the screen led to an early closure of the temporal window, but a saccade causing an identical displacement relative to the retina did not interrupt integration (Drissi-Daoudi et al., 2020). In another experiment (Drissi-Daoudi et al., 2021), one of the flanking lines was missing in several frames, causing the perceived motion stream to be discontinuous. The occluder that covered the missing lines was either present on the screen (in this case, the line seemed to go behind the obstacle and then reappeared from behind it) or not wasn't. Vernier offsets were placed both before and after the gap. With the occluder present it seemed that the motion of the line was continuous (although some of the movement was invisible), and two offsets were more likely to be integrated, while in the absence of the occluder they were more often perceived separately. Also, unconscious integration windows seem to be longer under increased processing load condition: when between the two offsets whose integration being tested, there are another two offsets that cancel each other (Vogelsang et al., 2021).

All these data show that percepts can enter consciousness with a delay of up to several hundred milliseconds, and the duration of such a delay may depend on the nature of the input information.

Criticism and defense of discrete models

Here we review the main directions of criticism of discrete models and the answers to this criticism offered in the two-stage model proposed by M. Herzog et al. (2020).). The idea of discrete units of different sizes at the level of unconscious processing and conscious perception is discussed as a possible option for resolving the existing contradictions.

One of the main criticisms toward discrete models is that it is impossible to determine the universal duration of a discrete unit of perception as its estimate depends on the method used (Herzog et al., 2016; White, 2018). For example, thresholds for nonsimultaneity detection and temporal order judgments vary depending on a large number of factors, and in some studies can reach very small values (e.g. 6 ms) (White, 2018). The perceptual moment concept assumes that its size can change due to stimuli characteristics, but problems arise even when examining highly similar effects on the same stimuli. For example, the flash lag effect (see section «Behavioral Evidence for Discrete Perception») and the Fröhlich effect are quite close to each other (the latter differs in that the static stimulus is in the position from which the second one starts to move). The model based on the «perceptual moment» hypothesis suggests that the average magnitude of both effects depends on the «moment» duration (Schneider, 2018). Morrow & Samaha (2022) replicated both effects in the same sample using the same stimuli but found no correlation between their magnitudes.

Ronconi et al. (2017) have also compared two similar effects: the two-flash fusion (that occurs when two stimuli appear at the same position) and the apparent motion (when stimuli appear at the different positions). They studied the link between the occurrence of integration (as opposed to perceiving them separately) and prestimulus phase of EEG-oscillations. For both effects, a relationship was observed, but for different EEG bands and at different time points relative to the stimuli onset (for the two-flash fusion, integration could be the most accurately predicted based on the phase of alpha band oscillations (8–10 Hz) 300–400 ms before the first stimulus onset; for the apparent motion, the most predictive value had theta oscillations (6–7 Hz) 400–500 ms before the onset (Ronconi et al., 2017) – *author's note*), which suggests different sizes of a discrete unit.

White (2018) sees a problem with EEG evidence of discrete perception in the wide range of frequencies associated with various perceptual effects (including low-frequency oscillations from 1 Hz). As P. A. White points out, if the hypothesis of multiple perceptual cycles (proposed by the authors of one of the discrete approaches: VanRullen & Koch, 2003; VanRullen, 2016) is correct and sampling is carried out at different frequencies at once, then this indicates the discreteness of some local processing mechanisms, rather than conscious perception as such.

Another line of criticism is related to the fact that integration, including postdictive integration, can be executed continuously, within «sliding» rather than discrete temporal windows. For example, simple effects that demonstrate the limited temporal resolution of perception can be easily explained without the perceptual moment hypothesis, with low-pass filter algorithms (signal «blurring») (VanRullen & Koch, 2003). Allport (1968), who was one of the first to propose the continuous perceptual moment idea (the «Travelling Moment» model), notes that the existence of a period within which all events are perceived as simultaneous does not necessarily indicate discreteness. The D. A. Allport's model implies that some function similar to a moving average, is applied to data. All events separated by the time less than the «travelling moment» duration are perceived as simultaneous, but this relation is not transitive.

Fekete et al. (2018) suggest that integration within a «sliding window» can explain even more complex postdictive effects, which are usually used as evidence for the discrete perception. The authors point out that continuous integration can also result in a postdictive formation of a conscious percept. As an example, they give a smoothing model in which some feature value at a specific time point is calculated taking into account both earlier data and data received for a certain period after this point.

The authors of one of discrete approaches (Herzog et al., 2020) in response to this criticism argue that the sliding temporal windows hypothesis does not explain the phenomenology of postdictive effects, since it suggests that percepts in this case does not enter consciousness fully formed but morph over time. For example, in the case of apparent motion, if the continuous integration model is correct than at first, one static dot must be rendered conscious, then a moving dot, and then a second static dot. But that's not what happens. In reality, only one moving dot is perceived.

In some cases, visual illusions can be modified postdictively in a complex way depending on the stimuli context (Noguchi et al., 2007). In our opinion, it also speaks against continuous interpretation. Moreover, idea of sliding temporal windows, renders impossible the coherence check or other control of a prepared interpretation before it reaches conscious (more on this in the next paragraph).

The first direct experimental evidence for the discrete integration windows has also been appearing (Drissi-Daoudi et al., 2019; see section «Studies of long-lasting postdictive effects»).

In our opinion, a successful reconciliation of contradictions between continuous and discrete processing is proposed in the two-stage model of M. Herzog et al. (2020). According to this model, the discrete percept formation is preceded by a long period of unconscious processing, during which the brain operates with data in a rather high temporal resolution. The problem of multiple temporal resolutions is not relevant here, since they are inherent to individual unconscious processing mechanisms and do not determine the size of the conscious perception discrete unit (which is larger anyway).

This model contradicts the hypothesis of a universal perceptual moment, within which all temporal information is lost, but it may be compatible with existence of discrete sampling in local processes of unconscious processing. For example, the authors admit that unconscious processing may involve the predictive coding (Herzog et al., 2020), which, as mentioned earlier, may require discrete sampling (Chota, 2020).

The negative choice theory and prospects for its application

Here we describe a perspective of V. M. Allakhverdov's theory on the discreteness of perception. This approach explains discretization through the need to control the prepared representation before

it becomes conscious. An idea is proposed that the discrete unit of conscious perception depends on the complexity of control operations. We look at several effects known in cognitive psychology that have similar temporal dynamics, which, according to our hypothesis, can be explained by stimuli falling into one unconscious processing window or into different ones.

Similar to the proposed two-stage model (Herzog et al., 2016; Herzog et al., 2020), but a different understanding of discrete perception follows from V. M. Allakhverdov's negative choice theory (Allakhverdov, 2000; Allakhverdov et al., 2019; Allakhverdov, 2021). According to this approach, before being rendered conscious, the prepared representations are checked for coherence. Those of them that cannot be consistently integrated with the other (for example, because they contain alternative interpretations of the same data) are marked in a certain way («negatively chosen») and do not enter consciousness. Thus, in this approach, discretization is associated with the need to control the prepared interpretation before it becomes conscious.

According to this model, the negative choice has an aftereffect. It is assumed that stimuli processed, but not integrated into conscious representation («negatively chosen»), are less likely to enter consciousness afterwards, therefore being rendered conscious with a delay.

This theory also suggests the existence of unconscious processing windows with a variable duration. But if in Stroud's model (1967) the duration of a discrete unit of perception varies depending on the physical parameters of stimuli, and in the two-stage model of M. Herzog et al. (Herzog et al., 2016; Herzog et al., 2020) it depends on the amount of time necessary to construct their meaningful interpretation than according to the V. M. Allakhverdov's theory, this duration is affected by the complexity of control operations performed before conscious perception. Moreover, this approach assumes that it is conscious perception that is discrete, while unconscious processing might be continuous. What is novel in this case is the idea that the «window» closes with the procedure of control of the prepared representation for consistency. The task of such control is to select information to enter consciousness.

There are not so many experimental studies of the factors determining the duration of unconscious processing windows (see section «Studies of long-lasting postdictive effects»). We assume that when considering this issue, it might be helpful to examine some other effects known in cognitive psychology that have a «suitable» temporal dynamic, which can be associated with stimuli falling into the same unconscious processing window or into different ones: such as a masked priming effect or the attentional blink. The idea that a conscious perception discrete unit depends on the complexity of control operations may in our opinion have the potential to explain the dynamics of such effects.

For example, the following dynamics of masked priming can often be observed: with short prime-target stimulus onset asynchronies (SOAs), unconscious primes positively affect target perception (positive priming), while as the SOA increases, this influence reverses and a counterintuitive negative priming effect occurs. So far the dynamics of masked priming has been best studied for simple stimuli that require binary responses (e.g. right / left arrow; square / diamond), i.e. for apparently simple tasks. Positive priming in such tasks occurs with prime-target SOAs lesser than 80 ms, and negative priming can be observed when SOA increases to 100–200 ms (e.g., Eimer, 1999; Schlaghecken & Eimer, 2000; Boy & Sumner, 2010; Atas & Cleeremans, 2015). And though such dynamics most often appear in simple tasks implying automated responses, the negative priming effect is observed primarily for the slow responses (Eimer, 1999; Atas & Cleeremans, 2015; Wang et al., 2020) i.e. for those that as can be assumed involve conscious control. This is in line with the negative choice theory suggesting that the delay in this case occurs at the stage when target stimuli enter consciousness and should not be observed in automated responses.

For more complex stimuli such as words or numbers, masked negative priming is often registered at longer SOAs of 500–600 ms (e.g., Yee, 1991; Milliken et al., 1998; Frings & Wentura, 2005; Filippova & Kostina, 2020). The dynamics of this type of priming is less studied, but in a number of experiments we can see the same pattern as for simple tasks: a change from positive to negative priming effect with an increase in the SOA (Ortells et al., 2003; Ortells et al., 2001; Yee, 1991).

As we propose, the factor determining the change of priming from positive to negative with an increase in the SOA may be that the prime and the target fall not into the same unconscious processing window, but into different ones. In this case, the minimum SOA required for the negative priming to occur is associated with the unconscious processing window length, that varies depending on the specific experimental conditions. For instance, it takes more time for the negative priming to form when simple stimuli with a binary response are presented under difficult perceptual conditions (e.g., peripherally or smaller in size) (Lingnau & Vorberg, 2005). Moreover, when a smaller set of complex stimuli is used (e.g. repeated many times words in Frings & Eder, 2009; D'Angelo & Milliken, 2012), the negative priming is likely to form earlier, at intervals comparable to those for which this effect is observed when simpler stimuli are used (in the above examples already at SOAs of 140–200 ms). This suggests that the time of the negative priming occurrence may be affected by the number of stimuli used in the experiment (which should also be related to the complexity of control in identification task).

Similar temporal dynamics can be observed in the attentional blink studies using the rapid serial visual presentation (RSVP) paradigm. In this paradigm several stimuli (usually letters, numbers, words or images) some of which are targets being presented sequentially for a short time (e. g., for 100 ms or less). Subjects most likely miss the second target when it is presented 200–500 ms after the first one (Shapiro et al., 1997; Dux & Marois, 2009). If the second target follows the first directly, it is usually successfully reported (e.g., Raymond et al., 1992). It can be suggested that the effect disappears when the first and second target fall into the same temporal processing window (a number of attentional blink models offer a similar interpretation, according to which two targets that follow each other without a lag can fall into one «temporal episode» or «attention episode», though the nature of these episodes is understood differently in different models (for review see Snir & Yeshurun, 2017), – *author's note*). For example, it was shown that the following factors diminish the attentional blink effect: the visual similarity of two targets (Makarov & Gorbunova, 2020), the possibility to integrate them into a single visual image (Falikman, 2001; Akyürek & Wolff, 2016), belonging of three successively presented targets to a single category (Di Lollo et al., 2005) (for example, if three target letters or numbers are presented in a row, subjects report the third target as often as the first one, but if the second target belongs to a different category the reportabitily of the third target decreases (Di Lollo et al., 2005), – *author's note*), the instruction to name a pair of targets together, rather than separately (Ferlazzo et al., 2007).

According to the negative choice theory, both the switch from positive to negative priming and the attentional blink can be a result of the control mechanism that is triggered at the end of the temporal unconscious processing window. The discussed effects can be a useful material for research of the factors determining the duration of the temporal window, in particular, the hypothesized influence of the control task complexity.

The mentioned studies differ in too many parameters to be able to draw firm conclusions from them. Therefore, it seems appropriate to create procedures allowing to vary the complexity of the control task, which would be useful to test experimentally the hypothesis about the possibility to change the duration of the conscious perception discrete unit. The result of this approach might be the unification of various phenomena in a broader context, which is a promising prospect.

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Information about conflicts of interest

The authors have no conflicts of interest to declare.