PERCEIVING OBJECTS MOVING THROUGH SPACE AND TIME: "WHERE" AND "WHEN" ARE INTERTWINED

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Abstract

Different theories on motion perception have been based on the evidence that the perceptual system makes errors in the localization of objects. Most of these theories are based on the assumption that inherent delays lead to mislocalization when things move or, more generally, when things change: errors in time translate into spatial errors. Even if this assumption has been often criticized, and evidence has been found against this view, it is still widely accepted. Data from behavioural, psychophysical and physiological studies suggest instead a dynamical inter-relationship between space and time, the rules of which are still to be revealed.

Traditionally psychophysical studies on motion perception are interested in testing the correspondence between the physical and perceived (i) position, (ii) velocity and (iii) trajectory. As often happens in perceptual studies, "errors" are considered as a powerful tool to understand how the perceptual system deals with the physical world. In this perspective, different theories on motion perception have been based on the evidence that the perceptual system makes errors in the localization of objects. Typically these errors have been observed at "event's boundaries" (i.e. at the beginning and the vanishing positions of a moving object) or when we compare the position of a flashed target with the instantaneous position of a continuously moving one (or one that appears to be moving even though no change occurs in the retinal image).

These errors are respectively: i) the Fröhlich effect (Fröhlich, 1923): a mislocalization forward in the direction of motion of a moving object starting point (typically observed when a moving line enters a window); ii) the Backward mislocalization (Actis-Grosso & Stucchi 2003): a mislocalization opposite to the direction of motion of a moving object starting point; iii) the Representational Momentum (Hubbard & Bharucha, 1988): a mislocalization forward in the direction of motion of a moving object vanishing point and (iv) the Flash-lag effect (Nijhawan, 1994): in which subjects perceive a flashed item that is co-localized with a moving item as trailing behind the moving item.

Several models have been proposed to explain these errors (e.g. Baldo & Klein 1995, Krekelberg & Lappe, 1999, Brenner and Smeets, 2000, Eagleman and Sejnowski, 2000, Murakami, 2001) the majority of which are based on the assumption that inherent delays – such as the typically estimated latency of about 100 ms needed for the transmission of the nervous signal along the visual pathways (De Valois & De Valois, 1991), or the time for central processing of the visual signal (see Krekelberg & Lappe,

1999) – lead to mislocalization when things move or, more generally, when things change: errors in time translate into spatial errors. For this reason localization errors could be considered both errors in the perceived "space" (i.e. non-correspondence between perceived and physical space) or errors in the perceived "time" (i.e. non-correspondence between perceived and physical "time"). We suggested (e.g. Actis-Grosso, Bastianelli, Stucchi, 2008) referring to these errors as spatio-temporal mislocalizations.

The idea behind all these models is that the sensory-motor system extrapolates the position of moving targets despite neural latency. However, authors often underline the importance of defining space and time from a psychological point of view in order to account for these effects. In fact, if for a physicist the classic definition of motion is "something that changes its position over time", for a visual scientist it raises some important aspects regarding the correspondence of the physical event and its perceived counterpart: the position of the object, its distance from the observers, its speed and its acceleration. This means that studies focusing on movement have often considered motion *per se*, as a distinct variable from space and time.

Currently, this point of view is generally accepted. As a matter of fact, our visual system has movement receptors but no temporal or space receptors. Thus, spatio-temporal mislocalizations have been considered a challenge for all the models that refer to movement as being disconnected from physical/perceived space and time.

Therefore, in order to account for these mislocalizations it seems necessary to consider movement as the link between space and time. In fact the recently proposed models take into account the perceptual system as a function of physical space and of time transposition.

The problem stems on the fact that space and time seem to be "pure concepts", without any apparent counterpart in the physical domain. In other words, in order to understand the physical world, it seems necessary for the human mind to reason in terms of space and time. However, even from a physical point of view, it becomes necessary to consider space and time as intertwined: thus, it should not be surprising that the relation between space and time is still an open problem for studies on perception. The fact that a dot, which appears (or disappears) in a certain position, is in fact perceived in another position could be reported simply as a *spatial* dislocation or as the spatial counterpart of a *temporal* delay. The majority of the interpretations given to this kind of dislocation (mainly for the FLE) are in terms of time, implying a sort of correspondence between physical time and psychological time, whereas physical and psychological time are completely different, as shown by a lot of studies.

The study of spatio-temporal mislocalizations seems to be the key to understand how the perceptual system manages to translate the continuous changes i) of the physical world and ii) of sensory stimulation.

The empirical studies that have focused their interest on the perceived position of a moving stimulus (i.e. the starting point, the vanishing point and the position of a moving object when a flash is given) have shown that the magnitude of the perceptual mislocalizations depends on kinematics such as the speed and the acceleration of the moving object (Freyd & Finke, 1985; Hubbard, 1995; Eagleman & Sejnowski, 2000; Thornton, 2002; Actis-Grosso & Stucchi, 2003). However, it has been shown that observers reported errors in the perception of speed (Bozzi, 1992), for example judging as constant a velocity, which is accelerated in fact (Runeson, 1974). Thus, studying the perceived velocity and kinematics, and how they might influence spatio-temporal mislocalizations, becomes a crucial factor.

In a series of experiments aimed at testing the role of velocity on the magnitude of spatio-temporal mislocalizations, we found (Actis-Grosso et al., 2008) that this role is different when a spatial reference is introduced: we performed four experiments where both velocity modulations (Experiments 1-3) and absolute velocity (Experiment 4) were used as independent variables, focusing on the role of velocity modulation for both starting and vanishing point mislocalizations. The empirical investigation began with experiments designed to study the effect of a target's absolute velocity at the beginning and at the end of a motion on mislocalizations and to test their magnitude (experiment 1-2); in Experiment 3 different modulations of velocity on the central part of the trajectory were tested for both at the starting and at the ending point. Finally, in experiment 4 we changed the typical experimental paradigm to obtain an estimation of starting point as accurately as possible. With the method of constant stimuli, we investigated the presence of a threshold for target absolute velocity on starting point localization. The presence of a reference system, as shown in Thornton (2002) and in Actis Grosso and Stucchi (2003), improves the precision of responses, i.e., the reduction of dispersion of responses provides a much more accurate measure: in this experiment our goal was to measure the threshold value for velocity.

The different paradigm changed the experimental setting, because a *spatial* reference system was introduced. What we found was that, in the experiments where only velocity was varied, the results were different with respect to those of Experiment 4, where it was introduced a spatial reference. We believe that the reference system has completely changed the perceived setting: the presence of a reference system recalibrated the measurement system. We concluded that in the perception of motion space and time have an interdependence that is still unknown.

These experiments were also aimed at testing a model proposed by Actis Grosso & Stucchi (2003) to account for spatial mislocalizations. That model puts forward a relationship between space and time, underlining the role played by "static anchors" (i.e. occluding surfaces). The visual system could rely on these static anchors as a reference point from which the extrapolation of a moving object's spatial position could be started. The idea that the presence of an occluding surface (i.e. a spatial reference system) has an influence on the perceived time is based not only to the presence of different localizations errors at motion starting point when a spatial reference system is present (i.e. a "window" in the Fröhlich effect) or absent (i.e. backward mislocalizations), but also on the tunnel effect (Burke, 1952), where the duration of object persistence changes depending on the presence of an occluding surface along its path. The tunnel effect had received surprisingly little attention, but in our view it puts in evidence that, in a perceptual world which is continuosly changing, a static spatial reference is also used to cope with real-time changes.

Regarding the relation between space and time in spatio-temporal mislocalizations, Kerzel and Gegenfurtner (2003) - in a work where observers fixed on a central mark while the target moved in the lower visual field and disappeared at an unpredictable position - put forward two relevant issues. The first one is that the position of a moving target could be extrapolated in two different ways: by a fixed spatial distance across target velocity or by a fixed temporal interval. In the first case, the effect of velocity on the spatial error should be absent and the extrapolated time should consequently decrease with increasing velocity. In contrast, if the position was extrapolated by a constant time interval, there should be an effect of velocity on the spatial error but there should be no effect on temporal error. Their results did not provide a clear answer. The spatial error increased by 0.5 degrees with increasing velocity, and extrapolated time decreased with increasing velocity. The second relevant issue concerns whether the extrapolation happens at an early stage or at a later one. Thus, they asked observers to fixate on a target that was surrounded by a large frame. In the condition ‘real motion’, the target moved while the frame was stationary. In the condition ‘induced motion’, the target was stationary, and the frame was moved. In complete darkness, observers found it hard to distinguish between the two types of motion.

It is interesting to notice that the problem of the relations between space and time has recently emerged also in physiological studies. Evidence from physiological studies seems to suggest that the human eye concurrently codifies both position and velocity of a target already at a retinal level (Uchiyama, Goto, Matsunobu, 2001, Pearlman & Hughes, 1976), in which ON-OFF cells encode more specific stimuli than simply general movement: ON-OFF sequence of light intensity change are encoded with a spike pair with an interval of approximately 20 ms, “indicating that temporal coding is utilized in the vertebrate visual system as early as the retina” (Uchiyama et al., 2001, p. 611), as already predicted by Berry, Brivanlou, Jordan, & Meister (1999) from the precise timing of the spike trains of the retinal ganglion cells (see Carlini, Actis-Grosso and Pozzo in this issue). While in physics velocity is simply the time derivative of position and is treated as such, in physiology visual velocity is a primary dimension, no less fundamental than position. From the initial stage, our visual system has motion detectors and position detectors, ultimately contributing to motion maps and position maps in the cerebral cortex. In both types of map, cells have receptive fields. The position of a moving stimulus can be represented in two ways: by an instantaneous peak of neural activity in a position map, or by integration of a velocity signal. In smooth pursuit, it has been postulated (Priebe, Churchland, Lisberger, 2001) that motion-selective neurons with a particular speed tuning are responsible for motion perception, whereas the sequential activation of receptive fields leads to the perception of change in position (but note that the two can be perceptually dissociated in the motion aftereffect). Recently, some researchers have expressed reservations about the role of a receptive field map in localization (Krakelberg & Lappe, 2001), suggesting that velocity and position are represented together in the same neuronal population and are not always completely dissociable, as is suggested by several works (e.g. De Valois & De Valois, 1991; Nishida & Johnston, 1999; Whitney & Cavanagh, 2000): “Perhaps our conception of maps is too simplistic” (Schlag & Schlag-Rey, 2002).

In their explanation of the flash-lag, Krekelberg and Lappe (2002) and Eagleman and Sejnowski (2000) assume that an instantaneous stimulus position is computed by the brain by integrating velocity signals. Theoretically, this process takes more time than finding the peak of activity in a receptive field. First, integration is not instantaneous: it requires some sort of averaging over a defined period. Second, the results of the computation cannot be immediately available because they are based not on current data, but on data that follow the triggering event. Nonetheless, these results are referred to the only available time marker, which is the event itself (called subjective time, Rao, Eagleman & Sejnowski, 2001). Eagleman and Sejnowski (2000) created the term ‘postdiction’ to stress the possibility that some of our perceptions depend on future events.

Indeed, the models proposed to account how we successfully interact with moving objects can be divided into three main categories on the basis of the assumption that visual perception is considered as: *predictive*, *on-line* or *postdictive*. With the aim of testing the extrapolation into the future against interpolation of the past, Eagleman and Sejnowski (2000) suggested a series of psychophysical experiment. They concluded that only events after the flash determine perception. Thus, they proposed that visual awareness is postdictive, so that the percept attributed to the time of an event is a function of what happens in the ~80 ms following the event. In particular, the brain constructs a percept by combining an internal model of the world (based on recent history) with the current external input. How the brain combines these sources of information depends on the respective salience. Specifically, the degree to which the internal model is relied upon depends on how easy is to detect the moving object (Eagleman & Sejnowski, 2000). However, how internal models are set-up and which internal and external details are combined has not yet been clearly specified (Krakelberg & Lappe, 2001).

More recently, Eagleman and Sejnowski (2007) have modified their interpretation, suggesting motion signals bias position judgment. According to their modified view the instantaneous position judgement of a moving target is biased by motion signal that follow. This account would subsume that time and space are joined in visual perception and could not be studied separately. This point of view is in line with what Benussi proposed in 1907, according to which a spatial distance is perceived as being wider when the interval between successive stimuli is longer. The influence of time on perceived space is called the *Tau effect* (see Cermisoni, Actis-Grosso, Stucchi & Antonelli in this issue). The *Tau effect* is described by a space-time illusion demonstrated most simply by flashing three equidistant lights *A*, *B*, and *C* successively in the dark, with a shorter time interval between *A* and *B* than between *B* and *C*: this setting produces the space-time illusion that *A* and *B* are closer together in space than *B* and *C*. Some years later, Benussi (1913) reported the reverse phenomenon: the influence of the space on perceived time. This effect has been studied more extensively by Abe (1935) and by Hansel and Sylvester (1953), who dubbed it the *Kappa effect*: in this case, judging the interval duration between two lights A and B, the duration appears longer when the distance between the two sources is greater.

The theoretical consequences of the relation between space and time (such as the *Tau* and the *Kappa* effects) are that at a perceptual level it is impossible to divide space and time in terms of the perception of an object. The research shows that space and time are not perceived independently: judgements about time are influenced by spacing stimuli and spatial judgements are influenced by their timing. According to Benussi (1917), the theoretical consequences of these relations are not trivial. Both the *Tau* and *Kappa* effects reveal that the temporal parameter of an event could be converted into the spatial parameter by a sort of an unknown function. This position is curiously similar to the recent suggestion (Eagleman and Sejnowski, 2007) that it is pointless to try to separate space and time in experimental studies on visual perception: thus, it seems that after almost a century of research the field of motion perception has not made much progress.

Data from behavioural, psychophysical and physiological studies suggest a dynamical inter-relationship between space and time, the rules of which are still to be revealed. We think that studying spatio-temporal mislocalizations might rekindle our thinking about how the brain copes with real-time changes in the world.

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