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Review article

Being active over one's own motion: Considering predictive mechanisms in self-motion perception

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ABSTRACT

Self-motion perception is a key element guiding pilots' behavior. Its importance is mostly revealed when impaired, leading in most cases to spatial disorientation which is still today a major factor of accidents occurrence. Self-motion perception is known as mainly based on visuo-vestibular integration and can be modulated by the physical properties of the environment with which humans interact. For instance, several studies have shown that the respective weight of visual and vestibular information depends on their reliability. More recently, it has been suggested that the internal state of an operator can also modulate multisensory integration. Interestingly, the systems' automation can interfere with this internal state through the loss of the intentional nature of movements (i.e., loss of agency) and the modulation of associated predictive mechanisms. In this context, one of the new challenges is to better understand the relationship between automation and self-motion perception. The present review explains how linking the concepts of agency and self-motion is a first approach to address this issue.

1. Introduction

Self-motion perception is crucial for behavioral performance in many common tasks like maintaining standing balance, walking, or driving. It gives us the ability to follow the changes in our position dynamically in space and time, and to guide our movements and behavior relative to the external world. The relevance of self-motion perception is even more obvious when considering the control of a complex system like an airplane. In this context, pilots must constantly judge their position in space and the attitude of their aircraft with respect to the earth reference frame. Although it is assisted in the task by ever more sophisticated sensors, the misperception of self-motion is still today a cause of many accidents, a phenomenon commonly known as spatial disorientation. This perceptual phenomenon is due to the processing of sensory inputs which may, however, be inappropriate in some unusual environments (e.g. particular visual contexts or force field conditions, etc.) for specifying the agent's own motion in the earth reference frame with which he/she interacts. For example, during forward linear acceleration, the otoliths are stimulated in the same way as when the body tilts backwards (i.e., somatogravic illusion (Graybiel and Kellogg, 1966; Clément et al., 2001)), leading an operator to perceive an illusory climb of the aircraft. When spatial disorientation occurs, an operator may be tempted to intervene in an inappropriate manner on the current aircraft situation, with potentially deadly consequences. Since accidents due to spatial disorientation are hardly reduced (Gibb et al., 2011), one of the major challenges is therefore to better understand the sensory integration processes that underlie self-motion perception in order to avoid the exposure of pilots to spatial disorientation situations.

Another critical concern is the potential impact of the nature of motion in which an operator is engaged on his/her perception of self-motion. Particularly, the active or passive nature of motion raises the question of the associated mechanisms involved in motion perception. This question relates to the concept of agency since an agentive situation refers to a situation in which the operator exercises intentional control over an action and consequences (Haggard and Chambon, 2012). This issue finds an interesting echo in the operational context since automation technologies have an impact on the control the pilot has over the aircraft motion and besides, the level of agency he/she experiences (Berberian et al., 2012; Ueda et al., 2021). Particularly, although automation is supposed to be facilitative and safe, while optimizing task

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execution, its growing development raises questions about the emergence of "human factors" risks that are specific to it (Endsley and Kiris, 1995; Sheridan, 2002). Namely, concerns about alertness, engagement, fatigue, confidence, and more broadly attention and mental load (Young and Stanton, 2002; Young et al., 2015) that can alter the performance of the pilot in critical situations can be evoked. Thus, the challenge today is to reconsider the human as a full-fledged processor in the development loop of such tools that require interaction with the operator (Berberian, 2019). The aim is to keep the operator in agentive situations (e.g., in his/her device control) to optimize the interaction with the systems and possible takeovers.

Yet, most studies dealing with self-motion perception have focused on the perception of passive/unintentional displacement, i.e., non-agentive motion. To our knowledge, no study has so far considered the impact of agency on self-motion perception: *does a pilot perceive self-motion in the same way when the autopilot is engaged and when it is switched off?* Moreover, the question can be largely extended to other application domains such as, for example, the automotive industry. Therefore, we use the term 'pilot' here in a generic way, although we rely on the aviation domain to illustrate our point throughout this review. Overall, this review argues in general that visuo-vestibular integration and thus self-motion perception could be modulated during agentive (i.e., voluntary) action in any driving experience. Several elements point in this direction. First, the subjective construction of agency is based on predictive mechanisms and is associated with perceptual modulations such as sensory attenuation and intentional binding (Hughes et al., 2013). Conversely, it has been demonstrated that the agentive nature of a situation can help mobilize attentional mechanisms (Wen and Haggard, 2018) and may thus take part in the activation of top-down mechanisms.

Overall, these findings collectively suggest a potential role of mechanisms underlying the sense of agency on those involved in visuo-vestibular integration. A better understanding of this impact is of great importance to develop robust solutions to concrete problems including that of spatial disorientation. To that aim, the present review will successively address the following issues: integrative mechanisms (Parts I and II), perceptual implications (Parts III, IV and V), and applicative challenges (Part VI).

2. Multisensory integration for self-motion perception: being active as mostly unconsidered

An accurate perception of self-motion requires integrating environment-centered cues mainly provided by optic flow, and body-centered cues issued from vestibular, somatosensory inputs, and motor control activities (for reviews Cheng and Gu, 2018; Cullen, 2019). Many studies indicate that, to infer self-motion, the human brain has developed multisensory adaptive mechanisms that contribute to the perception of the world by combining redundant and complementary inputs from different senses, and thus compensating for sensory uncertainty (Ernst and Banks, 2002; Alais and Burr, 2004; Ernst and Bülthoff, 2004; Fetsch et al., 2013). To this purpose, the vestibular system has been mostly considered at the heart of the early stages of self-motion integration and has a privileged link with the visual inputs in the perceived motion direction (heading) (Gu et al., 2007; Butler et al., 2010; Fetsch et al., 2010; Gu et al., 2010; de Winkel et al., 2017), distance (Harris et al., 2000), as well as the structure and orientation of the environment travelled (Bertin and Berthoz, 2004; Brandt et al., 2005; Yoder and Taube, 2014).

Remarkably, visuo-vestibular integration has been extensively studied, both at the behavioral (Fetsch et al., 2009; Butler et al., 2010; MacNeilage et al., 2010; de Winkel et al., 2017; Ramkhalawansingh et al., 2018) and neurophysiological level (Gu et al., 2007; Gu et al., 2008; Morgan et al., 2008; Gu et al., 2010; Chen et al., 2011; Fetsch et al., 2012). Particularly, it has been largely explained by the theory of optimal integration (Fetsch et al, 2010, 2013; ter Horst et al., 2015). In this line, it appears as a weighted integration according to the reliability of each sensory input in two major aspects of self-motion perception, namely, displacement estimation (ter Horst et al., 2015) and heading discrimination (Gu et al., 2007; Gu et al., 2008; Morgan et al., 2008; Gu et al., 2010; Chen et al., 2011; Fetsch et al., 2012). As an example, Morgan and colleagues have demonstrated that the more the visual stimulation is degraded, the greater the weight of vestibular inputs (Morgan et al., 2008). Such integrative reweighting schemes were supported by numerous studies demonstrating that multisensory integration is extremely flexible and dependent on the nature of sensory inputs (Chen and Vroomen, 2013; Donohue et al., 2015; de Winkel et al., 2018; Zhao et al., 2018; Bruns, 2019; Shayman et al., 2020) and integrative laws have been proposed to account for this flexibility (Ohshiro et al., 2011; Carandini and Heeger, 2012; van Atteveldt et al., 2014; Ohshiro, 2017; Bauer et al., 2020).

Strikingly, these different works were mainly interested in the modulation of integrative mechanisms according to the properties of the environment (bottom-up mechanisms), but largely neglected the impact of the perceiver's internal state in the process (top-down mechanisms). Notably, the integrative foundations of sensory processing have been largely considered on the passive side, while sensory processing remains mostly active (Kveraga et al., 2007; Schroeder et al., 2010; van Atteveldt et al., 2014). In this vein, some authors stress the need for an active approach to perception, called "*Active sensing*" (Schroeder et al., 2010). This concept argues for *"increased emphasis on the study of sensory processes as specific to the dynamic motor/attentional context in which inputs are acquired"* (Schroeder et al., 2010). From a methodological point of view, the term "active" therefore refers to any situation in which an external event (stimulus) is the result of an intentional action by the participant.

Being an intentional actor of a sensory consequence has already received interest in studies investigating audio-visual perception (van Kemenade et al., 2016; Straube et al., 2017). However, when considering the visuo-vestibular integration, the state of the art remains largely focused on data collected during passive self-motion conditions (Cheng and Gu, 2018). Moreover, and quite surprisingly, the concept of active sensing has been rarely considered in relation to the concept of agency whereas these two concepts seem to largely overlap. An agentive situation indicates a situation in which the operator exercises intentional control over an action and its consequences (Haggard and Chambon, 2012). More particularly, a non-agentive or passive motion would correspond to a displacement whose set of characteristics is controlled by a system external to the one that perceives motion. In contrast, being active over one's own motion would refer to the state of being in an agentive situation with respect to the ongoing motion. A related question would then refer to how the agentive nature of control (passive versus active) impacts self-motion perception. The following section supports this claim by presenting several works highlighting predictive mechanisms which may underlie active versus passive sensory integration.

3. Being active over one's own motion: all a question of prediction?

Only a few works addressed the issue of being in control of our own motion and its consequences on visuo-vestibular integration. Particularly, some works highlighted the distinction between active and passive motion at the level of the vestibular nucleus for a specific population of neurons: the VO (*vestibular only*) neurons which have also been considered as the basis of self-motion (McCrea et al., 1999; Carriot et al., 2013). Specifically, for a given passive motion, up to 75 % response decrease can be observed in the active condition (McCrea et al., 1999). Further, Carriot et al. (2013) showed that attenuation of VO neurons' responses at the first stage of processing was specifically observed when the movement is consistent with the intention. Interestingly, this signal inhibition observed when the efference copy due to active motion matches current sensory inputs was observed both for rotation (Roy and Cullen, 2004) and translation (Carriot et al., 2013). Although these studies are confined to the animal model (e.g., *Macaca mulatta* monkeys), they clearly demonstrate a neurophysiological link between the vestibular system and the intentional control of self-motion. Strikingly, these works are the first to show that the vestibular system depends on predictive mechanisms. Since then, other works have extended this active-passive distinction to other brain structures and for several dimensions of movement (Rotation: Brooks and Cullen, 2013 (cerebellum); Dale and Cullen, 2019 (thalamus); Multidimensions: Carriot et al., 2015 (vestibular nuclei); Mackrous et al., 2019 (cerebellum)).

Based on these data, Brooks and Cullen (2019) go further than the *"Active sensing"* concept by talking about *"Predictive sensing"* considering specific signal processing in early vestibular pathways (Brooks and Cullen, 2019). The importance of predictive mechanisms for sensory, motor, and cognitive function has long been recognized. In the sensory domain, it has been suggested that prediction allows for more efficient processing of behaviorally relevant stimuli, particularly by allowing for cancellation of sensory input caused by our own movements (Sperry, 1950; von Holst and Mittelstaedt, 1950). More recently, several works highlighted the role of prediction at the neurophysiological level (Cullen, 2004; Sawtell and Williams, 2008; Sawtell, 2010). For example, Sawtell and Williams (2008) have demonstrated that (1) neurons in the electrosensory lobe (ELL) of weakly electric mormyrid fish generate prediction of the sensory consequences of the fish's own movements, (2) these predictions are used to minimize self-generated signals of predictable consequences of behavior. From that, they show how predictive adaptive filtering mechanisms enable selective encoding of behaviorally relevant sensory information depending on the origin of the signal to optimize perception Therefore, active coding falls in the well-established theoretical concept of perception for cognitive and computational neuroscience: Predictive coding (Huang and Rao, 2011; Rauss and Pourtois, 2013; Friston, 2018; Hohwy, 2020). Indeed, predictive coding admits that the brain is a predictive machine that constantly infers by combining internal generated predictions and external events, at different levels of integration (Walsh et al., 2020). The emergence of such a concept has finally led to a shift from the classical dichotomy of distinct top-down and bottom-up mechanisms to a cascading loop scheme (see Fig. 1 from Walsh et al., 2020). In this model, the internal predictions run through each hierarchical level when the prediction errors signals are sent back in the opposite direction (Hesselmann et al., 2010; Rauss and Pourtois, 2013; Walsh et al., 2020). Today, at both perceptual (Myers et al., 2020) and various cortical levels (Walsh et al., 2020), there is a growing set of evidence supporting this approach which underlines the key role that motor signals play in sensory processing through predictions (Brooks and Cullen, 2019). Here, action is considered as a main way to reduce uncertainty since it allows better outcomes predictions. Recent studies emphasize that the sensorimotor context may indeed sharpen the representations of expected outcomes and integrative mechanisms (Yon et al., 2018; Jagini, 2021). In this line, several authors suggested that active versus passive distinction in early processing may have an impact on the computation of spatial orientation and postural control by higher order structures (Roy and Cullen, 2004; Gu, 2018; Brooks and Cullen, 2019; Mackrous et al., 2019; Cullen and Wang, 2020; Cullen and Zobeiri, 2021).

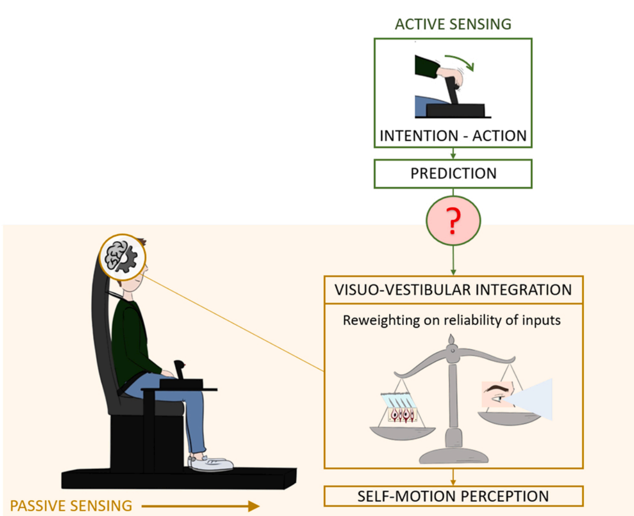

Fig. 1. Schematic representation of the main issue developed in the first chapter; Integrative Mechanisms (Parts I and II). In the first two parts, we present the main knowledge gathered on visuo-vestibular integration. From there, we argue the need to confront the predictive mechanisms, inherent to the control of motion, with the perception of an agentive (i.e., a voluntary) motion.

Accordingly, we support that the intentional nature of a motion is likely to modulate the visuo-vestibular integration mechanisms, notably through underlying predictive mechanisms (Fig. 1). Particularly, the framework of agency appears highly promising to consider the role of computational predictive mechanisms in the perceptual processes at work for an active observer. Although limited until now to other modalities of interest (e.g., auditory, visual or tactile), the body of knowledge gathered around this concept is very informative about the mechanisms involved in the perception of intentional actions.

4. Agency, prediction and perceptual consequences

The sense of agency describes the subjective feeling associated with controlling one's own actions and, through these actions, events in the outside world (Haggard and Tsakiris, 2009; Haggard and Chambon, 2012). Resulting from multiple signals (Synofzik et al., 2008), the sense of agency is largely and mostly explained by internal mechanisms. Particularly, the subjective construct of agency is recognized as intrinsically determined by the computational predictive mechanisms of human action control. In line with predictive coding, these mechanisms are generally explained through a comparator model (CM) (Frith et al., 2000; Blakemore et al., 2002) which is based on the intentional aspect of human action. Thus, according to the internal models theory (Wolpert and Kawato, 1998), an intentional action generates an efference copy (i.e., forward model) to produce a predicted state in parallel with the motor command (i.e., inverse model). This participates to the construct of an agentive internal state when the prediction of the sensory consequences of an action and the sensory feedback of this action are congruent/coherent.

Interestingly, these predictive mechanisms activated by our voluntary actions seem to be involved not only in the development of the subjective experience of control but also in the way we perceive the sensory consequences of our actions. This is illustrated by a well-known paradigm concerning the perception of time between the action and its sensory consequences: the Intentional Binding (IB) (Moore and Obhi, 2012 for review). IB refers to the subjective temporal compression experienced between a voluntary action and its external sensory consequences (e.g. sound feedback). A time interval that is only underestimated during a voluntary movement (Haggard et al., 2002; Haggard, 2005).

In addition to this temporal compression, perceptual modulations of the sensory consequences of the action are also observed. Historically, self-generated action is associated with central attenuation (Blakemore et al., 1998; Timm et al., 2014) that has been largely correlated with perceptual attenuation at auditive (Hughes et al., 2013), visual (Cardoso-Leite et al., 2010), tactile (Blakemore et al., 1999; Bays et al., 2006) or somatosensory level (Shergill et al., 2013). Conversely, recent studies show an increase in brain activity (Reznik et al., 2014; Reznik et al., 2015; Wen et al., 2018; Yon et al., 2018), which can, for example, be associated with a decrease in perceptual thresholds (Reznik et al., 2014). Thus, the neural activities of self-generated events can also be enhanced rather than inhibited (Roussel et al., 2013). Overall, there is then a set of observable operations that take place at different levels of analysis and that lead to either attenuation or enhancement of sensory pathways. Altogether, these observations support the concept of predictive coding since they suggest that both cancellation and activation at different levels may help to sharpen sensory integration of sensory outcomes (Wen et al., 2018; Yon et al., 2018).

If, as previously exposed, the intentional nature of an action may impact perceptual mechanisms, its direct influence on multisensory integration itself remains far less documented. How to explain the impact of the agentive nature of an action and predictive mechanisms in the light of multisensory integration processes and their ponderation? This issue is specifically addressed in the next section.

5. Being active over one's own motion: consequences on multisensory integration

To date, multisensory mechanisms have not been directly and explicitly confronted with the one of agency. Recently, van Kemanade and her colleagues (2016) engaged the reflection since they specifically investigated multimodal consequences of our actions at the audio-visual level. Beyond a significantly better performance in the bimodal task (i.e., lowered audio-visual detection thresholds), this study reveals an increase in performance in the active condition. Moreover, the advantage of being active is even more obvious when occurring within a time window of almost 200 ms after the action. Interestingly, this is in line with the time window of agency (Wen, 2019). This confirms that the benefit of being active can be expressed as long as the consequences of the action occur in a time window consistent with the task at hand (Berberian et al., 2012). More importantly, being active allows for greater sensitivity to sensory inputs when they are presented simultaneously. This is reflected by a shortening of the perceived delay between the action and its synchronous sensory consequences. Therefore, the agentic state would derive its perceptual optimality when 1) the sensory consequences are presented synchronously with the action and 2) when sensory consequences are themselves synchronized.

This is consistent with the experience of agency since it is a part of human perception that mobilizes a reweighting integration associated with the intention-action-effect loop to increase the causality between action and consequences (Kawabe et al., 2013). The phenomenon of intentional binding is a perfect illustration. Beyond that, it is also expressed by a potentiation of multisensory integration serving a better sensitivity. Interestingly, a recent study went further by investigating the neural correlates of predictive multisensory action consequences, using fMRI (Straube et al., 2017). Specifically, they associated a suppression of the BOLD signal in the auditory and visual cortical areas with predictive mechanisms linked to the multisensory consequences of one's own action (Straube et al., 2017). Interestingly, this is consistent with the low-level inhibition already mentioned above and found at the vestibular level in the case of active movement (for review Cullen and Taube, 2017). Taken together, these works demonstrated that better multimodal integration during voluntary is dependent on prediction. However, why and how being active seems to potentiate multisensory integrative mechanisms for increasing performance remains to be questioned.

Here we speculate that the weighting mechanisms of sensory inputs are partly ruled by action-related intentions and predictions. Recent studies have shown that active self-motion largely decreases vestibular activity in the brainstem, cerebellum (Mackrous et al., 2019; see Cullen and Taube, 2017 for review), thalamus (Dale and Cullen, 2019) or cortex (Frank et al., 2016) to inhibit conflicting vestibular signals for postural balance (Cullen, 2019) or visual tracking (Frank et al., 2016). These results give a glimpse of the reweighting dynamics that can take place during multisensory integration in response to the intended action of an operator. Therefore, our main claim is that being active would elicit a strengthening of the mechanisms underlying multisensory integration in favor of relevant inputs. This would occur in order to reinforce the causality of the consequences of an action (Jagini, 2021) (Fig. 2).

Although this statement is reasonably supported by the body of knowledge mentioned above, there are still open questions to solve. For instance, the inner mechanism (at a cellular level?) underlying the influence of agency upon multisensory integration is still not well understood. In addition, which contexts other than direct motor output issued from the action generated could favor such integrative modulations? The following section focuses on how attention is also prime factor determining the influence of an agentive state over self-motion perception.

6. Being active over one's own motion: from prediction to attention

In addition to motor involvement, agency is also associated with a better commitment to the task (Caspar et al., 2016), with the mobilization of attentional mechanisms (Wen and Haggard, 2018). Attention can be defined as the neural process by which the brain enhances the representation of relevant task inputs by reducing external noise from irrelevant inputs (Schroeder et al., 2010). Therefore, attention shares with prediction the act of sharpening relevant cues to the task at hand. Besides, it has recently been proposed to consider them together, although these two notions are classically evoked separately (Schröger et al., 2015). In their review, the authors clarified the relations between prediction and attention and firstly outlined that prediction and attention are different mechanisms. Consistent with predictive coding (Friston, 2010, 2012; Bastos et al., 2012; Walsh et al., 2020), prediction aims at making inferences about the causes of sensory input and their expected accuracy, while attention is involved in optimizing the accuracy of the sensory input and regulating the gain of prediction errors. Second, prediction and attention remain closely related for three main reasons: (i) In a hierarchical view, attention modulates the sensory signals that depend on the underlying predictions and reveal the prediction error. (ii) Perceptual inference also consists in making inferences about the expected accuracy of the contents, by attentional modulation that increases the gain of anticipation signals. (iii) Increasing the gain allows a more efficient update of the model and, thus, better prediction.

Then, a strong connection between prediction and attention is to be assumed when considering their impact on multisensory integration (van Atteveldt et al., 2014; Hartcher-O'Brien et al., 2017; Ferrari and Noppeney, 2021). Moreover, predictive coding has also recently been proposed as a theoretical framework for multisensory integration for self-motion perception (Krala et al., 2019). According to recent findings, it can be assumed that such prediction-attention mechanisms potentiate the multisensory integration of cues relevant to a task at hand (Jensen et al., 2020). This is supported by the work of Donohue et al. (2015) exploring the interaction between attentional cueing and multisensory (audio-visual) integration using a bounce/stream paradigm. The principle of this paradigm is to make two circles evolve towards each other until they overlap, before they dissociate again. Under strictly visual stimulation the two circles are usually perceived as merging into each other when their paths cross. However, when a sound is added together when they merge, they are more commonly perceived as bumping into each other (the auditory bounce effect). On this basis, Donohue and his colleagues have shown that increasing the predictability of an event through a cue increases the auditory bounce effect since participants early orient their attentional focus to the right place. This is finally in agreement with other works explaining that the predictability of a target helps limit the interference of irrelevant information during integration (Jensen et al., 2020). Thus, orienting the attentional focus in an anticipatory manner facilitates the integration of relevant inputs (Lunn et al., 2019).

As in the work of van Kemenade et al. (2016), the effect appears stronger when sensory inputs are synchronous. Therefore, attention would derive its perceptual optimality regarding sensory integration when 1) the sensory consequences are predictable and 2) when sensory

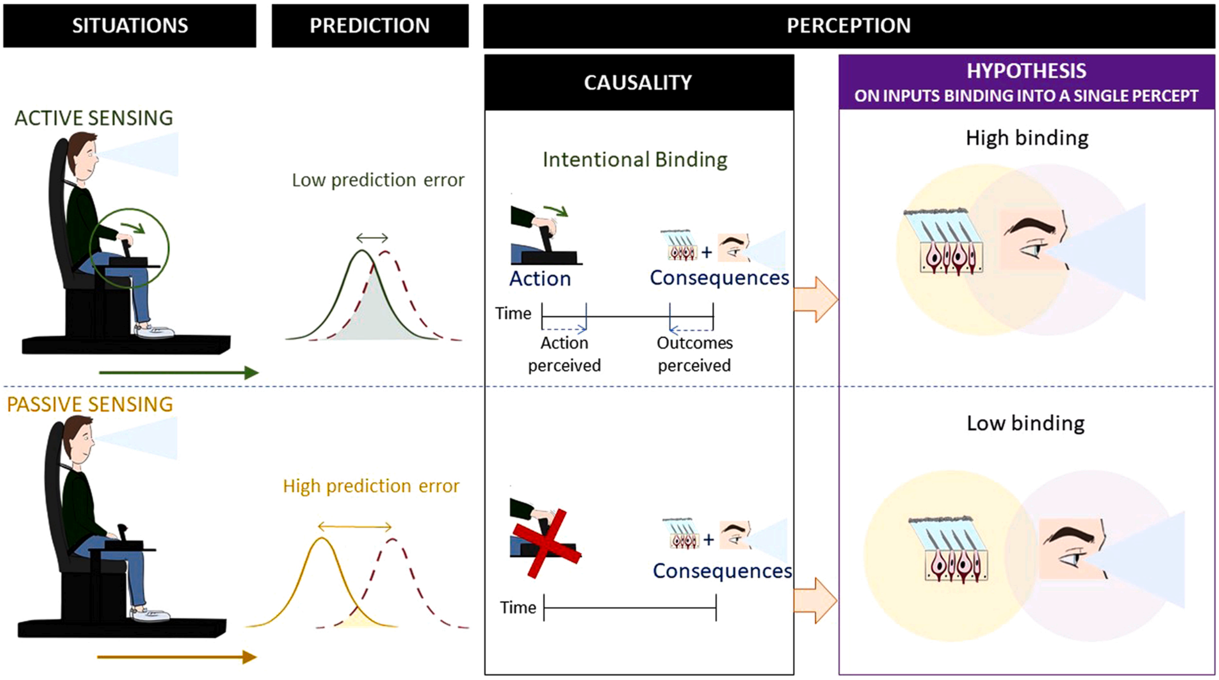

Fig. 2. Schematic representation of the key message developed in the second chapter; perceptual implications (Parts III, IV and V) and associated hypothesis. From part III to IV, we expose to what extent agency is a nice approach to consider the predictive mechanisms involved in self-motion perception. Also, in the light of some recent seminal works we outline hypotheses as to the impact on self-motion perception.

consequences are themselves synchronous. Taken together, these studies suggest a perceptual advantage of motor (van Kemenade et al., 2016) or attentional (Donohue et al., 2015) engagement in the ability to integrate sensory information into a single percept. This advantage might rely on a narrowing of the time window for integration and a better binding of relevant inputs (cf., Figures 6 and 8 of van Kemenade et al., 2016 and

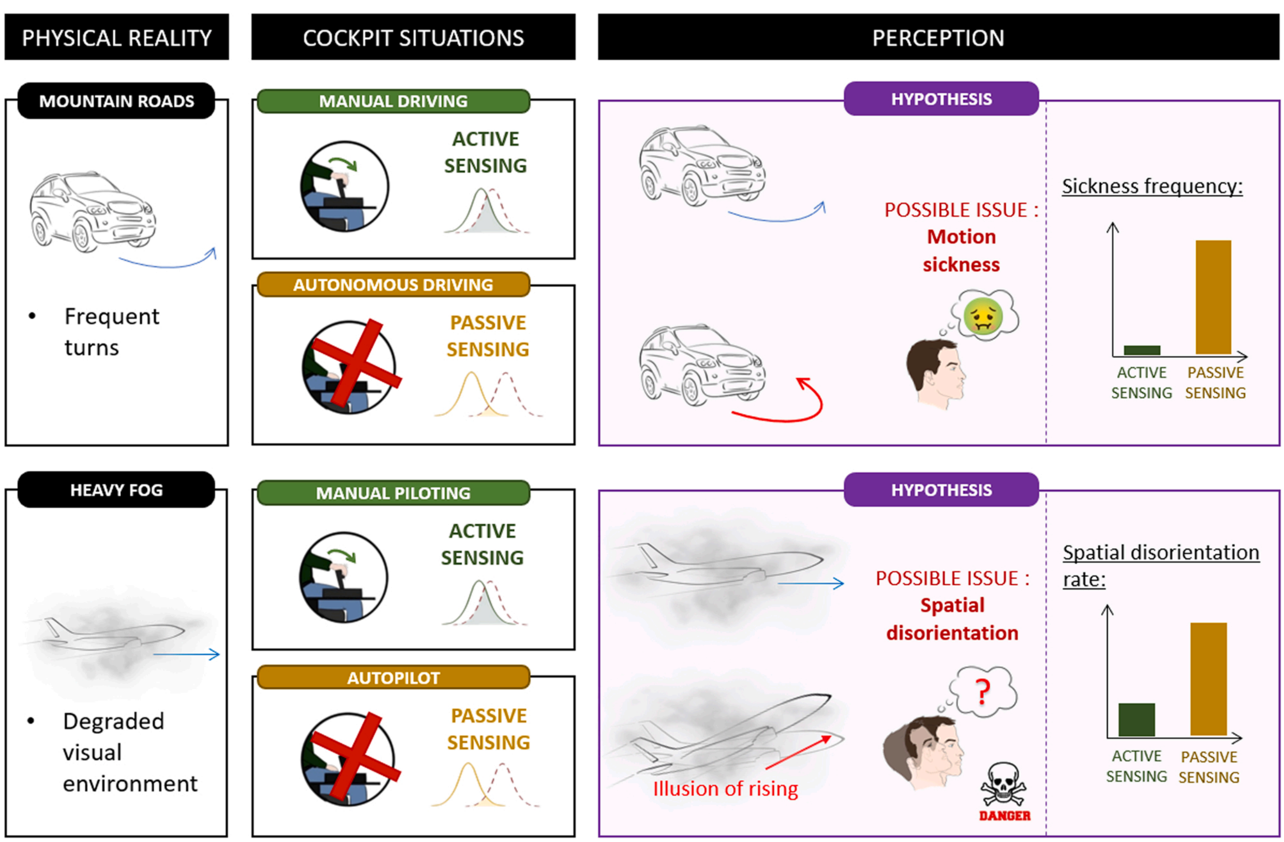

Fig. 3. Schematic representation of some examples of applicative challenges evoked in the last chapter; Applicative challenges (Part VI). In the last part, we illustrate to what extent the body of knowledge discussed in the present review could shed light on concrete field problems.

Fig. 3 and 4 of Donohue et al., 2015). Consistent with *Active sensing*, both motor and attentional mechanisms may be part of the reweighting process of relevant inputs for self-motion perception .

Above all, we see the high implication of the predictability of the situation in the integration of relevant information. Moreover, predictability is now recognized as a reinforcer of the internal agentive state (Tanaka and Kawabata, 2021). Remarkably however, this link has been mostly ignored when considering self-motion perception. Therefore, we propose to focus future studies at the level of the integration of the self-motion perception. Interestingly few studies point in this direction since they demonstrate attention implication at different levels of integration and perception for self-motion. First, it has recently been shown that visuo-vestibular integration depends on the main integrative operations of integration that are well-known to be modulated by attention (Ohshiro et al., 2011; Ohshiro, 2017). Second, some studies seem to suggest the impact of attention on self-motion perception (Berger and Bülthoff, 2009). However, too little has been done and we regret the lack of additional studies linking this theoretical field to self-motion. All the more so as the questions raised so far are of major importance from an application point of view. This is the subject of the next section.

7. Self-motion, agency and technological implications

In the previous sections, we emphasized the strong implication of the predictability of the situation in the integration of relevant information. We have also argued that the set of top-down mechanisms involved in an agentive situation allows a better integration of relevant cues. But how might this impact on human behavior, and more particularly on human performance in operational situations? In our introduction, we highlighted the growing importance of automation in aeronautical systems and the importance of spatial disorientation. The assumed link between the integration of visual-vestibular information, the predictability of the situation and the active nature of motion could therefore become critical.

A recent accident seems relevant in this respect. This concerns a helicopter stationary flying with the autopilot mode activated (CRDP-Air Reco-2014-023-A). One of the two skids slightly hit an obstacle and caused the aircraft to deviate below the pilots' perceptual threshold. However, the autopilot rectified the position of the aircraft with a kinetic above the perceptive threshold of the pilots. Only perceiving the correction displacement without being aware of the initial incident, the pilot then made an inappropriate correction to the actual position, resulting in the crash of the rotorcraft and the death of all the passengers. This accident illustrates first of all the difficulty that the pilot may have in perceiving slight movements of the aircraft when these are of weak and induced by the environment (i.e., not voluntary). Interestingly, this accident also illustrates how unexpected movements generated by an automatism can lead to a wrong perception of our body orientation in space. In this sense, the correction generated by the crew is highly indicative. The pilot thus took into account the vestibular information indicating the rolling motion of the rotorcraft but was unable to integrate the visual information necessary to understand the movement induced by the pilot assistance systems the rolling motion of the aircraft.

Such a case raises two interdependent concerns related to the optimization of management assistance systems in this kind of critical situations. First, one may address the possible modulation of the initial estimation or of the spatial disorientation according to the internal state of the pilot (agentive versus non-agentive). To what extent could being involved in the control loop compensate for this misperception? Second, one can also question to what extent a better adaptation of the systems could avoid an inappropriate intervention of the operator (announcement of the correction, better adapted correction gains of the automatic pilot).

More and more studies show that the more the situation is predictive, the better this optimization is expressed (Donohue et al., 2015; Jensen et al., 2020). Moreover, the field of agency has taken up the question and recent studies showed that predictability can be associated with a better feeling of control (Wenke et al., 2010; Sidarus, Chambon and Haggard, 2013). Therefore, making a system more predictable seems to help keeping the operator in a certain level of control while optimizing his perception of the inputs relevant to the task. Part of this question is motivated by the fact that automation of systems tends to remove the pilot from his/her control loop (Endsley and Kiris, 1995), and to lower his/her agentive internal state through a loss of predictive mechanisms of control of the action (Berberian et al., 2012). From this, one of the ways advanced recently to optimize systems is to make them predictable and thus reduce the opacity for the operator.

Particularly, part of the theoretical field of agency defends that a better cooperation and a reduced opacity can be reached by sharing intentions of the system in order to keep the pilot in control of the ongoing steering (Sebanz et al., 2003; van der Wel, 2015). Indeed, some works have recently shown that reducing the opacity of a system by exposing its intentions can also lead to an increased sense of control (Le Goff et al., 2018). The main argument is that it allows the operator to interpret the actions of the system as contributing to the control of the vector and not as an external disturbance that must be corrected. A part of the challenge would thus be to reconsider the human factor as an essential part of the system by reintegrating it into the driving process (Berberian, 2019). For all the reasons mentioned so far, we argue that extending the research on agency to the scope of motion perception would help overcome certain critical situations in flight.

Furthermore, focusing on the development of systems around agentive internal state of the operator and predictability of automation would participate both in a better performance through optimized integration of relevant inputs and in a better internal state estimation for the operator. For instance, a guided motor involvement may increase the level of confidence (Gajdos et al., 2019; Siedlecka et al., 2019). Also, it seems that transparency about the coherence between a decision and its consequences increases the confidence reported in this choice (Siedlecka et al., 2020). Therefore, increasing the predictability and transparency of the system would also help increase the operator's confidence in his/her control leading to a better acceptability of the system (Vantrepotte et al., 2022).

Finally, part of this confidence would result from the reduction of uncertainty in man-machine cooperation. However, uncertainty is a source of stress and may alter decision confidence (Heereman and Walla, 2011). It is known that an extreme level of stress may alter both the level of control (Yoshie and Haggard, 2013) and attention (Sänger et al., 2014). Therefore, we can also assume that responding to the problem of system opacity would also influence the impact of stress in critical situations that may alter control performance. Indeed, stress is already well recognized as a strong modulator of the general hormonal state. Multiple studies have therefore studied the impact of these hormonal modulations on performance in various tasks and in several populations (Wetzel et al., 2006; Kahng et al., 2007; Sauerland et al., 2016; Langer et al., 2020; Zhu et al., 2022). However, some aspects relative to stress influence on human-machine interactions have been also largely neglected (Sauer et al., 2019). Therefore, one of the avenues for future studies would be to evaluate the predictability of stressful events on the internal stress state of the operator, as it has been recently demonstrated in a driving task (Kerautret et al., 2022).

8. Conclusion

An agentive situation makes it possible to reduce uncertainty in favor of information relevant to the task. We argue that it implies the mobilization of motor and/or attentional predictive mechanisms. The purpose of these mechanisms is to reweight sensory inputs and increase the causality between the action and the consequences (Jagini, 2021). However, only few studies addressed this issue in the framework of self-motion perception and its neurophysiological correlates (i.e.

visuo-vestibular integration). Indeed, only few integrative (Ohshiro et al., 2011; Ohshiro, 2017), neural (Carriot et al., 2013) and perceptual evidence (Berger and Bülthoff, 2009) of a motor or attentional impact have been reported. However, we point out here that the visuo-vestibular integration has been too rarely explored with all the aspects presented throughout this review. We therefore raise here the need to explore self-motion perception through motor and attentional contributions, considering the novel constraints associated to pilot assistance systems.

In a very exciting way, the current trends go in the direction of an exploration of the impact of agency on self-motion perception (see *"Active sensing", "Predictive coding"* concepts). We argue here that mechanisms involved during agentive situations may modulate both weighting and predictive mechanisms that are involved in multisensory integration of self-motion both at temporal and spatial integration level. From an applicative point of view, this raises the question of maintaining agentive internal states of the operator, especially during critical operational phases.

Finally, all the concepts presented in this review seem to be in line with current operational challenges, notably the one raised by the phenomenon of spatial disorientation in aeronautics. Furthermore, we believe that this new frame of research can be applied to other fields (e.g., automotive sector) and concrete applications (e.g. motion sickness) (Fig. 3).

Declarations of interest

None.

References

Alais, D., Burr, D., 2004. The ventriloquist effect results from near-optimal bimodal integration. Curr. Biol. 14 (3), 257–262. https://doi.org/10.1016/j.cub.2004.01.029.

Bastos, A.M., et al., 2012. Canonical microcircuits for predictive coding. Neuron 76 (4), 695–711. https://doi.org/10.1016/j.neuron.2012.10.038.

Bauer, A.-K.R., Debener, S., Nobre, A.C., 2020. Synchronisation of neural oscillations and cross-modal influences. Trends Cogn. Sci. 15.

Bays, P.M., Flanagan, J.R., Wolpert, D.M., 2006. Attenuation of self-generated tactile sensations is predictive, not postdictive. In: Lackner, J. (Ed.), PLoS Biology, 4, e28. https://doi.org/10.1371/journal.pbio.0040028.

Berberian, B. et al. (2012) Automation Technology and Sense of Control: A Window on Human Agency, PLoS ONE. Edited by M. Tsakiris, 7(3), p. e34075. Available at: https://doi.org/10.1371/journal.pone.0034075.

Berberian, B., 2019. Man-Machine teaming: a problem of agency. IFAC-Pap. 51 (34), 118–123. https://doi.org/10.1016/j.ifacol.2019.01.049.

Berger, D.R., Bülthoff, H.H., 2009. The role of attention on the integration of visual and inertial cues. Exp. Brain Res. 198 (2–3), 287–300. https://doi.org/10.1007/s00221-009-1767-8.

Bertin, R.J.V., Berthoz, A., 2004. Visuo-vestibular interaction in the reconstruction of travelled trajectories. Exp. Brain Res. 154 (1), 11–21. https://doi.org/10.1007/s00221-003-1524-3.

Blakemore, S.-J., Wolpert, D.M., Frith, C.D., 1998. Central cancellation of self-produced tickle sensation. Nat. Neurosci. 1 (7), 635–640. https://doi.org/10.1038/2870.

Blakemore, S.-J., Frith, C.D., Wolpert, D.M., 1999. Spatio-temporal prediction modulates the perception of self-produced stimuli. J. Cogn. Neurosci. 11 (5), 551–559. https://doi.org/10.1162/089892999563607.

Blakemore, S.-J., Wolpert, D.M., Frith, C.D., 2002. Abnormalities in the awareness of action. Trends Cogn. Sci. 6 (6), 237–242. https://doi.org/10.1016/S1364-6613(02)01907-1.

Brandt, T., et al., 2005. Vestibular loss causes hippocampal atrophy and impaired spatial memory in humans. Brain 128 (11), 2732–2741. https://doi.org/10.1093/brain/awh617.

Brooks, J.X., Cullen, K.E., 2013. The primate cerebellum selectively encodes unexpected self-motion. Curr. Biol. 23 (11), 947–955. https://doi.org/10.1016/j.cub.2013.04.029.

Brooks, J.X., Cullen, K.E., 2019. Predictive sensing: the role of motor signals in sensory processing. Biol. Psychiatry.: Cogn. Neurosci. Neuroimaging 4 (9), 842–850. https://doi.org/10.1016/j.bpsc.2019.06.003.

Bruns, P., 2019. The ventriloquist illusion as a tool to study multisensory processing: an update. Front. Integr. Neurosci. 13, 51. https://doi.org/10.3389/fnint.2019.00051.

Butler, J.S., et al., 2010. Bayesian integration of visual and vestibular signals for heading, 23–23 J. Vis. 10 (11). https://doi.org/10.1167/10.11.23.

Carandini, M., Heeger, D.J., 2012. Normalization as a canonical neural computation. Nat. Rev. Neurosci. 13 (1), 51–62. https://doi.org/10.1038/nrn3136.

Cardoso-Leite, P., et al., 2010. A new look at sensory attenuation: action-effect anticipation affects sensitivity, not response bias. Psychol. Sci. 21 (12), 1740–1745. https://doi.org/10.1177/0956797610389187.

Carriot, J., Brooks, J.X., Cullen, K.E., 2013. Multimodal integration of self-motion cues in the vestibular system: active versus passive translations. J. Neurosci. 33 (50), 19555–19566. https://doi.org/10.1523/JNEUROSCI.3051-13.2013.

Carriot, J., Jamali, M., Cullen, K.E., 2015. Rapid adaptation of multisensory integration in vestibular pathways. Front. Syst. Neurosci. 9. https://doi.org/10.3389/fnsys.2015.00059.

Caspar, E.A., et al., 2016. Coercion changes the sense of agency in the human brain. Curr. Biol. 26 (5), 585–592. https://doi.org/10.1016/j.cub.2015.12.067.

Chen, A., DeAngelis, G.C., Angelaki, D.E., 2011. Representation of vestibular and visual cues to self-motion in ventral intraparietal cortex. J. Neurosci. 31 (33), 12036–12052. https://doi.org/10.1523/JNEUROSCI.0395-11.2011.

Chen, L., Vroomen, J., 2013. Intersensory binding across space and time: a tutorial review. Atten. Percept. Psychophys. 75 (5), 790–811. https://doi.org/10.3758/s13414-013-0475-4.

Cheng, Z., Gu, Y., 2018. Vestibular system and self-motion. Front. Cell. Neurosci. 12, 456. https://doi.org/10.3389/fncel.2018.00456.

Clément, G., et al., 2001. Perception of tilt (somatogravic illusion) in response to sustained linear acceleration during space flight. Exp. Brain Res. 138 (4), 410–418. https://doi.org/10.1007/s002210100706.

Cullen, K.E., 2004. Sensory signals during active versus passive movement. Curr. Opin. Neurobiol. 14 (6), 698–706. https://doi.org/10.1016/j.conb.2004.10.002.

Cullen, K.E., 2019. Vestibular processing during natural self-motion: implications for perception and action. Nat. Rev. Neurosci. 20 (6), 346–363. https://doi.org/10.1038/s41583-019-0153-1.

Cullen, K.E., Taube, J.S., 2017. Our sense of direction: progress, controversies and challenges. Nat. Neurosci. 20 (11), 1465–1473. https://doi.org/10.1038/nn.4658.

Cullen, K.E., Wang, L., 2020. Predictive coding in early vestibular pathways: Implications for vestibular cognition. Cogn. Neuropsychol. 37 (7–8), 423–426. https://doi.org/10.1080/02643294.2020.1783222.

Cullen, K.E., Zobeiri, O.A., 2021. Proprioception and the predictive sensing of active self-motion. Curr. Opin. Physiol. 20, 29–38. https://doi.org/10.1016/j.cophys.2020.12.001.

Dale, A., Cullen, K.E., 2019. The ventral posterior lateral thalamus preferentially encodes externally applied versus active movement: implications for self-motion perception. Cereb. Cortex 29 (1), 305–318. https://doi.org/10.1093/cercor/bhx325.

Donohue, S.E., Green, J.J., Woldorff, M.G., 2015. The effects of attention on the temporal integration of multisensory stimuli. Front. Integr. Neurosci. 9. https://doi.org/10.3389/fnint.2015.00032.

Endsley, M.R., Kiris, E.O., 1995. The out-of-the-loop performance problem and level of control in automation. Hum. Factor.: J. Hum. Factor. Ergon. Soc. 37 (2), 381–394. https://doi.org/10.1518/001872095779064555.

Ernst, M.O., Banks, M.S., 2002. Humans integrate visual and haptic information in a statistically optimal fashion. Nature 415 (6870), 429–433. https://doi.org/10.1038/415429a.

Ernst, M.O., Bülthoff, H.H., 2004. Merging the senses into a robust percept. Trends Cogn. Sci. 8 (4), 162–169. https://doi.org/10.1016/j.tics.2004.02.002.

Ferrari, A., Noppeney, U., 2021. Attention controls multisensory perception via two distinct mechanisms at different levels of the cortical hierarchy. In: Summerfield, C. (Ed.), PLOS Biology, 19, e3001465. https://doi.org/10.1371/journal.pbio.3001465.

Fetsch, C.R., et al., 2009. Dynamic reweighting of visual and vestibular cues during self-motion perception. J. Neurosci. 29 (49), 15601–15612. https://doi.org/10.1523/JNEUROSCI.2574-09.2009.

Fetsch, C.R., et al., 2012. Neural correlates of reliability-based cue weighting during multisensory integration. Nat. Neurosci. 15 (1), 146–154. https://doi.org/10.1038/nn.2983.

Fetsch, C.R., DeAngelis, G.C., Angelaki, D.E., 2010. Visual-vestibular cue integration for heading perception: applications of optimal cue integration theory: mechanisms of visual-vestibular cue integration. Eur. J. Neurosci. 31 (10), 1721–1729. https://doi.org/10.1111/j.1460-9568.2010.07207.x.

Fetsch, C.R., DeAngelis, G.C., Angelaki, D.E., 2013. Bridging the gap between theories of sensory cue integration and the physiology of multisensory neurons. Nat. Rev. Neurosci. 14 (6), 429–442. https://doi.org/10.1038/nrn3503.

Frank, S.M., et al., 2016. Cross-modal attention effects in the vestibular cortex during attentive tracking of moving objects. J. Neurosci. 36 (50), 12720–12728. https://doi.org/10.1523/JNEUROSCI.2480-16.2016.

Friston, K., 2010. The free-energy principle: a unified brain theory? 12.

Friston, K., 2012. Predictive coding, precision and synchrony. Cogn. Neurosci. 3 (3–4), 238–239. https://doi.org/10.1080/17588928.2012.691277.

Friston, K., 2018. 'Does predictive coding have a future. Nat. Neurosci. 21 (8), 1019–1021. https://doi.org/10.1038/s41593-018-0200-7.

Frith, C.D., Blakemore, S.-J., Wolpert, D.M., 2000. Abnormalities in the awareness and control of action. Philos. Trans. R. Soc. Lond. Series B: Biol. Sci. 355 (1404), 1771–1788. https://doi.org/10.1098/rstb.2000.0734.

Gajdos, T., et al., 2019. Revealing subthreshold motor contributions to perceptual confidence. Neurosci. Conscious. 2019 (1) https://doi.org/10.1093/nc/niz001.

Gibb, R., Ercoline, B., Scharff, L., 2011. Spatial disorientation: decades of pilot fatalities. Aviat. Space Environ. Med. 82 (7), 717–724. https://doi.org/10.3357/ASEM.3048.2011.

Graybiel, A., Kellogg, R.S., 1966. The inversion illusion in parabolic flight: Its probable dependence on otolith function. US Naval Aerospace Medical Institute, US Naval Aviation Medical Center.

Gu, Y., et al., 2010. Decoding of MSTd population activity accounts for variations in the precision of heading perception. Neuron 66 (4), 596–609. https://doi.org/10.1016/j.neuron.2010.04.026.
Gu, Y., 2018. Vestibular system and self-motion. Front. Cell. Neurosci. 12, 9.
Gu, Y., DeAngelis, G.C., Angelaki, D.E., 2007. A functional link between area MSTd and heading perception based on vestibular signals. Nat. Neurosci. 10 (8), 1038–1047. https://doi.org/10.1038/nn1935.
Gu, Y., Angelaki, D.E., DeAngelis, G.C., 2008. Neural correlates of multisensory cue integration in macaque MSTd. Nat. Neurosci. 11 (10), 1201–1210. https://doi.org/10.1038/nn.2191.
Haggard, P., 2005. Conscious intention and motor cognition. Trends Cogn. Sci. 9 (6), 290–295. https://doi.org/10.1016/j.tics.2005.04.012.
Haggard, P., Chambon, V., 2012. Sense of agency. Curr. Biol. 22 (10), R390–R392. https://doi.org/10.1016/j.cub.2012.02.040.
Haggard, P., Tsakiris, M., 2009. The experience of agency: feelings, judgments, and responsibility. Curr. Dir. Psychol. Sci. 18 (4), 242–246. https://doi.org/10.1111/j.1467-8721.2009.01644.x.
Haggard, P., Clark, S., Kalogeras, J., 2002. Voluntary action and conscious awareness. Nat. Neurosci. 5 (4), 382–385. https://doi.org/10.1038/nn827.
Harris, L.R., Jenkin, M., Zikovitz, D.C., 2000. Visual and non-visual cues in the perception of linear self motion. Exp. Brain Res. 135 (1), 12–21. https://doi.org/10.1007/s002210000504.
Hartcher-O'Brien, J., Soto-Faraco, S., Adam, R. (Eds.), 2017. A Matter of Bottom-Up or Top-Down Processes: The Role of Attention in Multisensory Integration. Frontiers Media SA (Frontiers Research Topics). Available at: https://doi.org/10.3389/978–2-88945–193-7.
Heereman, J., Walla, P., 2011. Stress, uncertainty and decision confidence. Appl. Psychophysiol. Biofeedback 36 (4), 273–279. https://doi.org/10.1007/s10484-011-9167-9.
Hesselmann, G. et al. (2010) 'Predictive Coding or Evidence Accumulation? False Inference and Neuronal Fluctuations', PLoS ONE. Edited by J. Lauwereyns, 5(3), p. e9926. Available at: https://doi.org/10.1371/journal.pone.0009926.
Hohwy, J., 2020. New directions in predictive processing. Mind Lang. 35 (2), 209–223. https://doi.org/10.1111/mila.12281.
von Holst, E., Mittelstaedt, H., 1950. Das reafferenzprinzip. Naturwissenschaften 37 (20), 464–476.
ter Horst, A.C., et al., 2015. Reliability-based weighting of visual and vestibular cues in displacement estimation. In: Ben Hamed, S. (Ed.), PLOS ONE, 10, e0145015. https://doi.org/10.1371/journal.pone.0145015.
Huang, Y., Rao, R.P.N., 2011. Predictive coding. WIREs Cogn. Sci. 2 (5), 580–593. https://doi.org/10.1002/wcs.142.
Hughes, G., Desantis, A., Waszak, F., 2013. Mechanisms of intentional binding and sensory attenuation: The role of temporal prediction, temporal control, identity prediction, and motor prediction. Psychol. Bull. 139 (1), 133–151. https://doi.org/10.1037/a0028566.
Jagini, K.K., 2021. Temporal binding in multisensory and motor-sensory contexts: toward a unified model. Front. Hum. Neurosci. 15, 629437 https://doi.org/10.3389/fnhum.2021.629437.
Jensen, A., et al., 2020. Interference of irrelevant information in multisensory selection depends on attentional set. Atten. Percept. Psychophys. 82 (3), 1176–1195. https://doi.org/10.3758/s13414-019-01848-8.
Kahng, A.B., Sharma, P. and Topaloglu, R.O. (2007) 'Exploiting STI stress for performance', in 2007 IEEE/ACM International Conference on Computer-Aided Design. 2007 IEEE/ACM International Conference on Computer-Aided Design, San Jose, CA, USA: IEEE, pp. 83–90. Available at: https://doi.org/10.1109/ICCAD.2007.4397248.
Kawabe, T., Roseboom, W., Nishida, S., 2013. The sense of agency is action–effect causality perception based on cross-modal grouping. Proc. R. Soc. B: Biol. Sci. 280 (1763), 20130991. https://doi.org/10.1098/rspb.2013.0991.
Keraurtet, L., Dabic, S., Navarro, J., 2022. Detecting driver stress and hazard anticipation using real-time cardiac measurement: a simulator study. Brain Behav. 12 (2) https://doi.org/10.1002/brb3.2424.
Krala, M., et al., 2019. Predictive coding in a multisensory path integration task: an fMRI study. J. Vis. 19 (11), 13. https://doi.org/10.1167/19.11.13.
Kveraga, K., Ghuman, A.S., Bar, M., 2007. Top-down predictions in the cognitive brain. Brain Cogn. 65 (2), 145–168. https://doi.org/10.1016/j.bandc.2007.06.007.
Langer, K., et al., 2020. Acute stress improves the effectivity of cognitive emotion regulation in men. Sci. Rep. 10 (1), 11571. https://doi.org/10.1038/s41598-020-68137-5.
Le Goff, K., et al., 2018. Agency modulates interactions with automation technologies. Ergonomics 61 (9), 1282–1297. https://doi.org/10.1080/00140139.2018.1468493.
Lunn, J., et al., 2019. Multisensory enhancement of attention depends on whether you are already paying attention. Cognition 187, 38–49. https://doi.org/10.1016/j.cognition.2019.02.008.
Mackrous, I., et al., 2019. Cerebellar prediction of the dynamic sensory consequences of gravity. e4 Curr. Biol. 29 (16), 2698–2710. https://doi.org/10.1016/j.cub.2019.07.006.
MacNeilage, P.R., et al., 2010. Vestibular Heading discrimination and sensitivity to linear acceleration in head and world coordinates. J. Neurosci. 30 (27), 9084–9094. https://doi.org/10.1523/JNEUROSCI.1304-10.2010.
McCrea, R.A., et al., 1999. Firing behavior of vestibular neurons during active and passive head movements: vestibulo-spinal and other non-eye-movement related neurons. J. Neurophysiol. 82 (1), 416–428. https://doi.org/10.1152/jn.1999.82.1.416.
Moore, J.W., Obhi, S.S., 2012. Intentional binding and the sense of agency: a review. Conscious. Cogn. 21 (1), 546–561. https://doi.org/10.1016/j.concog.2011.12.002.
Morgan, M.L., DeAngelis, G.C., Angelaki, D.E., 2008. Multisensory integration in macaque visual cortex depends on cue reliability. Neuron 59 (4), 662–673. https://doi.org/10.1016/j.neuron.2008.06.024.
Myers, J.C., Mock, J.R., Golob, E.J., 2020. Sensorimotor integration can enhance auditory perception. Sci. Rep. 10 (1), 1496. https://doi.org/10.1038/s41598-020-58447-z.
Ohshiro, T., 2017. A neural signature of divisive normalization at the level of multisensory integration in primate. Cortex 22.
Ohshiro, T., Angelaki, D.E., DeAngelis, G.C., 2011. A normalization model of multisensory integration. Nat. Neurosci. 14 (6), 775–782. https://doi.org/10.1038/nn.2815.
Ramkhalawansingh, R., Butler, J.S., Campos, J.L., 2018. Visual–vestibular integration during self-motion perception in younger and older adults. Psychol. Aging 33 (5), 798–813. https://doi.org/10.1037/pag0000271.
Rauss, K., Pourtois, G., 2013. What is bottom-up and what is top-down in predictive coding. Front. Psychol. 4. https://doi.org/10.3389/fpsyg.2013.00276.
Reznik, D., et al., 2014. Lateralized enhancement of auditory cortex activity and increased sensitivity to self-generated sounds. Nat. Commun. 5 (1), 4059. https://doi.org/10.1038/ncomms5059.
Reznik, D., Ossmy, O., Mukamel, R., 2015. Enhanced auditory evoked activity to self-generated sounds is mediated by primary and supplementary motor cortices. J. Neurosci. 35 (5), 2173–2180. https://doi.org/10.1523/JNEUROSCI.3723-14.2015.
Roussel, C., Hughes, G., Waszak, F., 2013. A preactivation account of sensory attenuation. Neuropsychologia 51 (5), 922–929. https://doi.org/10.1016/j.neuropsychologia.2013.02.005.
Roy, J.E., Cullen, K.E., 2004. Dissociating self-generated from passively applied head motion: neural mechanisms in the vestibular nuclei. J. Neurosci. 24 (9), 2102–2111. https://doi.org/10.1523/JNEUROSCI.3988-03.2004.
Sänger, J., et al., 2014. The influence of acute stress on attention mechanisms and its electrophysiological correlates. Front. Behav. Neurosci. 8. https://doi.org/10.3389/fnbeh.2014.00353.
Sauer, J., et al., 2019. Social stress and performance in human-machine interaction: a neglected research field. Ergonomics 62 (11), 1377–1391. https://doi.org/10.1080/00140139.2019.1652353.
Sauerland, M., et al., 2016. Stress, stress-induced cortisol responses, and eyewitness identification performance: stress and eyewitness identification performance. Behav. Sci. Law 34 (4), 580–594. https://doi.org/10.1002/bsl.2249.
Sawtell, N.B., 2010. Multimodal integration in granule cells as a basis for associative plasticity and sensory prediction in a cerebellum-like circuit. Neuron 66 (4), 573–584. https://doi.org/10.1016/j.neuron.2010.04.018.
Sawtell, N.B., Williams, A., 2008. Transformations of electrosensory encoding associated with an adaptive filter. J. Neurosci. 28 (7), 1598–1612. https://doi.org/10.1523/JNEUROSCI.4946-07.2008.
Schroeder, C.E., et al., 2010. Dynamics of active sensing and perceptual selection. Curr. Opin. Neurobiol. 20 (2), 172–176. https://doi.org/10.1016/j.conb.2010.02.010.
Schröger, E., Marzecová, A., SanMiguel, I., 2015. Attention and prediction in human audition: a lesson from cognitive psychophysiology. Eur. J. Neurosci. 41 (5), 641–664. https://doi.org/10.1111/ejn.12816.
Sebanz, N., Knoblich, G., Prinz, W., 2003. 'Representing others' actions: just like one's own. Cognition 88 (3), B11–B21. https://doi.org/10.1016/S0010-0277(03)00043-X.
Shayman, C.S., et al., 2020. Frequency-dependent integration of auditory and vestibular cues for self-motion perception. J. Neurophysiol. 123 (3), 936–944. https://doi.org/10.1152/jn.00307.2019.
Shergill, S.S., et al., 2013. Modulation of somatosensory processing by action. NeuroImage 70, 356–362. https://doi.org/10.1016/j.neuroimage.2012.12.043.
Sheridan, 2002. Humans and automation: system design and research issues. Kybernetes 32 (9/10). https://doi.org/10.1108/k.2003.06732iae.001.
Sidarus, N., Chambon, V., Haggard, P., 2013. Priming of actions increases sense of control over unexpected outcomes. Conscious. Cogn. 22 (4), 1403–1411. https://doi.org/10.1016/j.concog.2013.09.008.
Siedlecka, M., et al., 2019. Motor response influences perceptual awareness judgements. Conscious. Cogn. 75, 102804 https://doi.org/10.1016/j.concog.2019.102804.
Siedlecka, M., Paulewicz, B. and Koculak, M. (2020) Task-related motor response inflates confidence. preprint. Anim. Behav. Cognit. Available at: https://doi.org/10.1101/2020.03.26.010306.
Sperry, R.W., 1950. Neural basis of the spontaneous optokinetic response produced by visual inversion. J. Comp. Physiol. Psychol. 43 (6), 482–489. https://doi.org/10.1037/h0055479.
Straube, B., et al., 2017. Predicting the multisensory consequences of one's own action: bold suppression in auditory and visual cortices. In: Ahveninen, J. (Ed.), PLOS ONE, 12, e0169131. https://doi.org/10.1371/journal.pone.0169131.
Synofzik, M., Vosgerau, G., Newen, A., 2008. Beyond the comparator model: a multifactorial two-step account of agency. Conscious. Cogn. 17 (1), 219–239. https://doi.org/10.1016/j.concog.2007.03.010.
Tanaka, T., Kawabata, H., 2021. Sense of agency is modulated by interactions between action choice, outcome valence, and predictability. Curr. Psychol. 40 (4), 1795–1806. https://doi.org/10.1007/s12144-018-0121-3.
Timm, J., et al., 2014. Motor intention determines sensory attenuation of brain responses to self-initiated sounds. J. Cogn. Neurosci. 26 (7), 1481–1489. https://doi.org/10.1162/jocn_a_00552.
Ueda, S., Nakashima, R., Kumada, T., 2021. Influence of levels of automation on the sense of agency during continuous action. Sci. Rep. 11 (1), 2436. https://doi.org/10.1038/s41598-021-82036-3.

van Atteveldt, N., et al., 2014. Multisensory integration: flexible use of general operations. Neuron 81 (6), 1240–1253. https://doi.org/10.1016/j.neuron.2014.02.044.

van der Wel, R.P.R.D., 2015. Me and we: Metacognition and performance evaluation of joint actions. Cognition 140, 49–59. https://doi.org/10.1016/j.cognition.2015.03.011.

van Kemenade, B.M., et al., 2016. Predicting the sensory consequences of one's own action: first evidence for multisensory facilitation. Atten. Percept. Psychophys. 78 (8), 2515–2526. https://doi.org/10.3758/s13414-016-1189-1.

Vantrepotte, Q., et al., 2022. Leveraging human agency to improve confidence and acceptability in human-machine interactions. Cognition 222, 105020. https://doi.org/10.1016/j.cognition.2022.105020.

Walsh, K.S., et al., 2020. Evaluating the neurophysiological evidence for predictive processing as a model of perception. Ann. N. Y. Acad. Sci. 1464 (1), 242–268. https://doi.org/10.1111/nyas.14321.

Wen, W., et al., 2018. Enhanced perceptual processing of self-generated motion: evidence from steady-state visual evoked potentials. NeuroImage 175, 438–448. https://doi.org/10.1016/j.neuroimage.2018.04.019.

Wen, W., 2019. Does delay in feedback diminish sense of agency? A review. Conscious. Cogn. 73, 102759 https://doi.org/10.1016/j.concog.2019.05.007.

Wen, W., Haggard, P., 2018. Control changes the way we look at the world. J. Cogn. Neurosci. 30 (4), 603–619. https://doi.org/10.1162/jocn_a_01226.

Wenke, D., Fleming, S.M., Haggard, P., 2010. Subliminal priming of actions influences sense of control over effects of action. Cognition 115 (1), 26–38. https://doi.org/10.1016/j.cognition.2009.10.016.

Wetzel, C.M., et al., 2006. The effects of stress on surgical performance. Am. J. Surg. 191 (1), 5–10. https://doi.org/10.1016/j.amjsurg.2005.08.034.

de Winkel, K.N., Katliar, M., Bülthoff, H.H., 2017. Causal inference in multisensory heading estimation. In: Lappe, M. (Ed.), PLOS ONE, 12, e0169676. https://doi.org/10.1371/journal.pone.0169676.

de Winkel, K.N., Kurtz, M., Bülthoff, H.H., 2018. Effects of visual stimulus characteristics and individual differences in heading estimation. J. Vis. 18 (11), 9. https://doi.org/10.1167/18.11.9.

Wolpert, D.M., Kawato, M., 1998. Multiple paired forward and inverse models for motor control. Neural Netw. 11 (7–8), 1317–1329. https://doi.org/10.1016/S0893-6080(98)00066-5.

Yoder, R.M., Taube, J.S., 2014. The vestibular contribution to the head direction signal and navigation. Front. Integr. Neurosci. 8. https://doi.org/10.3389/fnint.2014.00032.

Yon, D., et al., 2018. Action sharpens sensory representations of expected outcomes. Nat. Commun. 9 (1), 4288. https://doi.org/10.1038/s41467-018-06752-7.

Yoshie, M., Haggard, P., 2013. Negative emotional outcomes attenuate sense of agency over voluntary actions. Curr. Biol. 23 (20), 2028–2032. https://doi.org/10.1016/j.cub.2013.08.034.

Young, M.S., et al., 2015. State of science: mental workload in ergonomics. Ergonomics 58 (1), 1–17. https://doi.org/10.1080/00140139.2014.956151.

Young, M.S., Stanton, N.A., 2002. Attention and automation: New perspectives on mental underload and performance. Theor. Issues Ergon. Sci. 3 (2), 178–194. https://doi.org/10.1080/14639220210123789.

Zhao, S., et al., 2018. Early cross-modal interactions underlie the audiovisual bounce-inducing effect. NeuroImage 174, 208–218. https://doi.org/10.1016/j.neuroimage.2018.03.036.

Zhu, X., et al., 2022. The effect of perceived stress on cognition is mediated by personality and the underlying neural mechanism. Transl. Psychiatry 12 (1), 199. https://doi.org/10.1038/s41398-022-01929-7.