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From fear of falling to choking under pressure: A predictive processing perspective of disrupted motor control under anxiety

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ABSTRACT

Under the Predictive Processing Framework, perception is guided by internal models that map the probabilistic relationship between sensory states and their causes. Predictive processing has contributed to a new understanding of both emotional states and motor control but is yet to be fully applied to their interaction during the breakdown of motor movements under heightened anxiety or threat. We bring together literature on anxiety and motor control to propose that predictive processing provides a unifying principle for understanding motor breakdowns as a disruption to the neuromodulatory control mechanisms that regulate the interactions of top-down predictions and bottom-up sensory signals. We illustrate this account using examples from disrupted balance and gait in populations who are anxious/fearful of falling, as well as 'choking' in elite sport. This approach can explain both rigid and inflexible movement strategies, as well as highly variable and imprecise action and conscious movement processing, and may also unite the apparently opposing self-focus and distraction approaches to choking. We generate predictions to guide future work and propose practical recommendations.

1. Introduction

Humans are proficient at performing an array of motor actions to interact with their environment. There are, however, a range of situations in which finely tuned motor control breaks down. One of the most common reasons for this disruption is the negative emotional state of anxiety (Beilock and Carr, 2001; Nieuwenhuys and Oudejans, 2012; Payne et al., 2018). Anxiety-induced disruptions range from feeling paralysed in the face of life-threatening stressors, to elite sporting performers 'choking' at a crucial moment, to fear of falling in older adults disrupting balance and paradoxically exacerbating the likelihood of a fall (Beilock and Carr, 2001; Vine et al., 2016; Young and Williams, 2015). In the present work we outline how predictive processing (PP) accounts of perception and action (Clark, 2013b; Friston, 2005; Friston et al., 2006; Hohwy, 2013; Seth, 2015) can be applied to understanding this interaction of motor control with aversive emotional states.[2] We outline how a PP paradigm can: i) explain a range of observed effects of anxiety on motor control; ii) enable a new understanding of the mechanisms behind this phenomenon; and iii) guide future empirical study and novel applied interventions. The aim of the current work is not to supplant existing theories or knowledge, but to provide an alternative perspective derived from neurocomputational theory. We suggest that a PP account may be able to unify existing cognitive and behavioural accounts of motor disruption, such as Attentional Control Theory (ACT; Eysenck et al., 2007), Reinvestment Theory (Masters and Maxwell, 2008), and the Explicit Monitoring Hypothesis (Beilock and Carr, 2001). We do not provide a highly detailed presentation of PP, or related ideas like the Free Energy Principle (see Bogacz, 2017; Friston et al., 2006), but instead aim to give an accessible overview within the context of applied motor control. Thus, we seek to first review and define key PP concepts like attention, precision, and motor control, and then describe how such accounts can be used to explain seemingly contradictory findings of motor performance breakdown under conditions of anxiety.

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[2] While there are important conceptual distinctions that can be drawn between terms like pressure, anxiety, fear and stress, here we treat them as broadly similar phenomena in relation to the common effect they have on prediction making and uncertainty (see Section 3).

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2. Predictive processing

The Predictive Processing Framework (PPF) views the brain and central nervous system as a hierarchical prediction engine which continuously generates a cascade of top-down hypotheses about the state of the body and the world, and who's central, guiding imperative is to minimise prediction error over time (Clark, 2013b; Friston et al., 2006, 2010). Although most straightforwardly presented in accounts of perception, this prediction error minimisation strategy also delivers accounts of action, attention, and other mental phenomena (e.g., imagery, inner speech) (Adams et al., 2013; Brown et al., 2011; Friston and Frith, 2015). Below we describe how predictive processing provides an account of perception through a process known as *perceptual inference*, and of action through *active inference*.

2.1. Perception and perceptual inference

According to the PPF, the brain makes inferences about the causes of its sensations based on an internal (generative) model that encodes 'beliefs' (probabilistic mappings) about how hidden states in the world generate sensory input (Clark, 2013b). Viewed from a Bayesian perspective, your brain's main task is to settle on the right hypothesis (model) about the world, given input (Clark, 2013b; Hohwy, 2013; Knill and Pouget, 2004). Since the world is a noisy and ambiguous place, any given sensory input is compatible with more than one hypothesis. What acts as a tiebreaker for selecting one hypothesis over another, is the prior probability (namely, the probability of the hypothesis independently of the sensory input). Prior beliefs generate predictions that are conveyed via top-down (backwards) connections. These predictions meet bottom-up (forward-flowing) sensory input, and any mismatch between the two (a 'prediction error') is 'explained away' by (mostly non-consciously) revising the selected hypothesis. On this view, what we perceive (our hypothesis selection) is thus not the world as it actually is, but the brain's best guess: a trade-off between the *fit* of the hypothesis with the given sensory input and its *prior probability*. The significance of this trade-off is that a hypothesis with a high prior probability can be selected even if it's not (relatively speaking) a good fit with input. Various perceptual effects like the Hollow Mask Illusion and Binocular Rivalry (including cross-modal effects like the McGurk effect) are illustrations of this (See Section 2.3 'Precision weighting' for further discussion).

The two elements of the Bayesian strategy and the prediction error minimisation implementation unite to form the following picture of perception: Our brains select hypotheses in a Bayes-optimal manner, based on how well those hypotheses minimise prediction error. Although these two elements often come together, our focus here is more on the prediction error minimisation implementation, for reasons that will become clear.

2.2. Action and active inference

The imperative for prediction error minimisation in selecting perceptual hypotheses (Friston et al., 2006) also applies to the motor system through a process known as active inference (Adams et al., 2013; Friston et al., 2010; Parr and Friston, 2019). In perceptual inference, prediction errors are minimised by the organism updating their model of the world to fit input. In active inference, however, the prediction is generated and then the (predicted) state of affairs is brought about as part of the prediction error minimisation imperative. While theoretically and computationally separable, in embodied agents, active and perceptual inference are in constant interaction. The PPF therefore does away with motor commands in the traditional sense, allowing proprioceptive predictions to fill that role instead (Adams et al., 2013; Shipp et al., 2013). When you raise your arm, you don't send a motor command to that effect, rather, you predict what it will be like to raise your arm, and your arm then lifts in fulfilment of the prediction (as failure to do so would result in a persistent prediction error signal). In other words, the actor generates a prediction of the exteroceptive and proprioceptive consequences of an intended action, with this prediction being self-fulfilled via the activation of classical reflex arcs (in an attempt to minimise prediction error; Adams et al., 2013; Brown et al., 2011). In the abstract, this process makes sense. Yet, a puzzle emerges. In perceptual inference, your brain's model-selection is constrained by input: your brain is forced to revise its model by the imperative to minimise prediction error. But how is prediction error kept at bay in active inference? How can your nervous system come up with hypotheses that it knows full well are not actualised? To answer this puzzle, we need to first return to perceptual inference and introduce the central notion of precision weighting.

2.3. Precision weighting

As discussed, sensory inputs are noisy and ambiguous, and this noisiness will vary from context to context (and from sense to sense). Optimising hypothesis selection involves not only making good predictions, but also making good estimations of the reliability (i.e., noise) of the incoming signal. In short, the lower the (informational) noise, the higher the trust in the input or inputs, and the greater impact they will have on the resulting percept. Hence, a good predictive engine must also make accurate second-order predictions; namely, how much to trust its own predictions. The process of flexibly increasing or decreasing the influence of prior beliefs relative to sensory input (or between competing priors or conflicting sensations) is a process known as *precision weighting.* Assigning high precision is appropriate in contexts of high informational quality, such as for visual information when driving on a clear day, while low precision weighting is appropriate in contexts of low informational quality (e.g., driving during low visibility on a foggy night). This second-order computational strategy of precision-weighting is realised in the brain through the precise control of neurotransmitters, especially dopamine (Friston et al., 2012b).

In sum, agents generate *precision estimates*, which are akin to second-order appraisals about the reliability of first-order beliefs (Fleming and Dolan, 2012; Yon and Frith, 2021). While these precision estimates occur mostly at lower levels and may not always be consciously accessible, human observers are near Bayes-optimal when they do report these meta-cognitive beliefs as confidence about first order probability estimates (Heilbron and Meyniel, 2019). Estimated precision can, however, be divorced from the true predictability of the world or the reliability of sensations, and agents may believe they can make precise predictions about events that are, in fact, unpredictable (and vice versa). Indeed, aberrant precision weightings have been proposed as explanations for clinical states such as Parkinson's (Friston et al., 2012b), addiction (Miller et al., 2020), schizophrenia and psychosis (Jeganathan and Breakspear, 2021), and autism (Arthur et al., 2020; Lawson et al., 2017). We will next consider how these precision estimates are controlled and the implications that this has for skilled motor performance.

2.4. Attention and precision

Within the PPF, attention is cast as a mechanism for context or state-dependent modulation of error signalling, via precision (Brown et al., 2011; Feldman and Friston, 2010; Limanowski, 2017; Mirza et al., 2019) (see green arrow in Fig. 1). Since increasing the neuronal gain of certain sensory or prediction error signals affords them additional weight in perceptual inference, precision weighting acts as an attentional spotlight (Clark, 2013a; Hillyard et al., 1998; Hohwy, 2020; Iglesias et al., 2013). For instance, bottom-up signalling of a deviation from predictions may be 'turned down' (i.e., attenuated) and treated as systemic noise in one context (particularly when predictions about the body or external world are viewed as highly precise), but multiplied when more attention is devoted to sensory signals or the environment appears less predictable

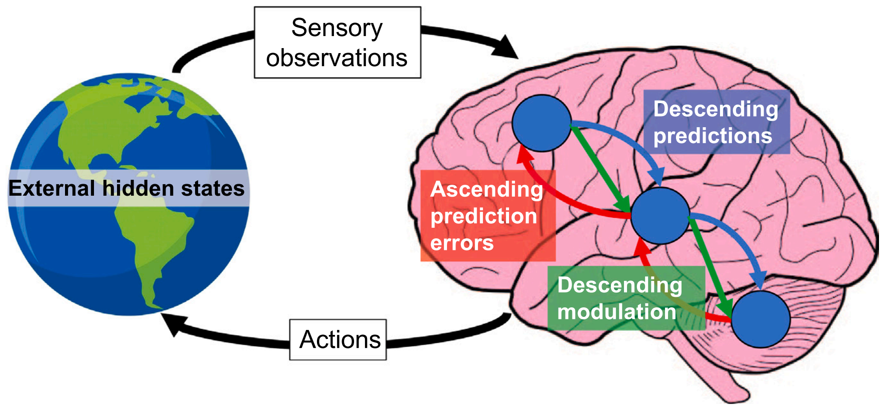

Fig. 1. Illustration of perceptual inference (where incoming sensory observations revise the world model) and active inference (where actions change the state of the world and the body to conform to predictions). During both, ascending error signals indicate when sensory input deviates from predictions. The strength of error signals is modulated by descending control of neural gain (aka precision weighting; see Section 2.3). This message passing scheme occurs at multiple hierarchical levels. Note: Figure does not necessarily reflect neuroanatomy; while descending predictions may come from prefrontal areas this depends on the type of predictions (e.g., motor).

(Clark, 2013a). As Clark (2018, p.522) notes, "*high-precision errors enjoy greater post-synaptic gain and (hence) increased influence. Conversely, even a large prediction error signal, if it is assigned extremely low precision, may be rendered systemically impotent, unable to drive learning or further processing*". This idea is nicely illustrated by the finding that a highly precise, yet inaccurate, prior about impending respiratory symptoms can trigger a perceptual experience of breathlessness even in the absence of any corresponding sensory input (Janssens et al., 2009).

In short, these frameworks propose that prediction errors can be resolved in one of three ways. First, we can update the prediction model itself. Next, prediction errors can be suppressed by downweighting or attenuating sensory input. Finally, prediction errors can be resolved by bringing about the predicted state (through either amplifying sensory input or performing the action required to generate the predicted sensory consequences). The brain must therefore calculate on a millisecond-by-millisecond basis how much weight to afford to sensory input and predictions (as well as how much weight to afford to one specific sensory input over another). This (mostly non-conscious) process is achieved by estimating the precision of incoming signals, in any given moment.

2.5. Precision is integral to action initiation and motor control

We now return to predictive processing accounts of motor commands and the central role for precision in the control of motor actions (Brown et al., 2011; Limanowski, 2017; Parr, Limanowski et al., 2021). As discussed, the 'prediction error minimisation' imperative accounts for both perception and action, just by switching around the 'direction of fit'. Hence motor control involves a delicate balance between active and perceptual inference, movement, and monitoring. The puzzle for understanding action, then, is: *how, if prediction errors are automatically minimised, can we generate the counterfactual hypotheses that correspond to motor commands?*

The answer is: by turning the precision of the counterfactual proprioceptive hypotheses right down, so that they no longer have sufficient influence to drive the action (Adams et al., 2013; Friston et al., 2012a). Attention (in the PPF sense) towards the sensory consequences of action is therefore temporarily suspended and, by virtue, the prediction errors that would otherwise elicit movement are suppressed (i.e., "I am not moving, despite my prediction that I would move). In effect, the prediction and the action become temporarily 'decoupled' by the reduction in precision. This decoupling is brief in the context of motor commands but can be more long-lived in the context of imagery (motoric or sensory). What happens next, is that a large surge of precision from dopamine in the midbrain (Friston et al., 2012b) is required to initiate action. Parkinson's, characterised by dopamine dysfunction, is an illustration of when this forced recoupling goes awry.

This 'decoupling' function illustrates the fundamental role that precision modulation plays in motor control, where we must predict not only the sensory consequences of movement but also the anticipated dispersion around this expectation (Kanai et al., 2015; Parr, Limanowski et al., 2021). The strength of proprioceptive predictions, and of the returning prediction errors, will determine the way in which actions are deployed and adjusted over time. With attention cast as a mechanism of precision modulation of error signalling (Brown et al., 2011; Mirza et al., 2019; Parr, Sajid et al., 2021) it is clear that attention will influence both motor predictions and how prediction errors affect moment-to-moment motor adjustments (Brown et al., 2011; Limanowski, 2017; Parr, Limanowski et al., 2021). As such, attention can boost or constrain the gain of sensory feedback during motor actions, as in other sensory modalities (Handy and Khoe, 2005; Hillyard et al., 1998; Limanowski, 2022). Consequently, the effect of attention on motor predictions is vital to successful execution of well learned motor skills (Brown et al., 2011); but as we will discuss, may also be the root of motor performance disruptions.

3. Anxiety is a state of generalised uncertainty

In PP formulations, emotions are intimately tied to inferences about motor and physiological states (Barrett, 2017; Clark et al., 2018; Wilkinson et al., 2019). Within PP accounts, anxiety – which is traditionally described as a negative emotional response to threat consisting of cognitive worry and physiological arousal (Eysenck, 2013) – is recast as a state of hypervigilance where the world is viewed as more uncertain and the agent can no longer predict the absence of threats with confidence (Cornwell et al., 2017; Grupe and Nitschke, 2013). When the world is unpredictable, previous learning about hidden states and causal regularities is less reliable, creating a constant uncertainty in which the brain is unsure about its predictions (Barrett and Satpute, 2013; Clark et al., 2018; Cornwell et al., 2017; Grupe and Nitschke, 2013; Lawson et al., 2021; Seriès, 2019). For instance, imagine that you hear rustling in the bushes outside your window at night. Typically, you would infer that this noise is caused by a harmless wild animal, however a recent news report about a spate of burglaries has made you anxious – and less certain – about the cause of the noise. In this instance, your prior beliefs ("this noise is most likely caused by a harmless animal") would be afforded reduced precision, and you would become hypervigilant to incoming sensory information (e.g., can you see a human-like shape outside? Can you hear footsteps in your garden?).

A high-level belief that the world is unpredictable or volatile subsequently influences the precision of all other beliefs within the cortical hierarchy (Yon and Frith, 2021). This descending control of precision weighting leads (initially, at least) to a state where prediction making is less certain and sensory errors dominate. For instance, anxious hypervigilance in the example above means you are more likely to notice the rustling in the bushes in the first place, even before attempting to infer its cause. In some scenarios this is a functional response for faster threat responding (which is suggestive of its evolutionary origins; Behrens et al., 2007), but in others, excessive attention to sensory information can be detrimental, particularly for fine motor control (Masaki et al., 2017; Moser et al., 2013). In addition to this descending influence of higher-level beliefs, lower-level uncertainty about the presence of threats could also initiate the anxious state (e.g., the perception of persistent unidentified rustling in the bushes). The mechanism behind these precision modulation effects is tied to the neurobiology of the anxious state and the effect of neurotransmitters, like noradrenaline, on the post-synaptic gain of error signals in response to environmental change (Hasselmo et al., 1997; Lawson et al., 2021).

Clark, Watson, and Friston (2018) describe anxiety not only as a state of uncertainty, but as a generalised expectation of uncertainty (about potential threats in the world and our ability to anticipate them) that is held with low precision. This means that the organism is unsure about their environment, but not yet certain that the environment is *perpetually* unpredictable. As a result, anxious agents seek to reduce the perceived unpredictability of the world, and the associated uncertainty about their perceptions, either through action or revising their beliefs. The nature of the anxious state means, however, that they are rarely able to do so (Grupe and Nitschke, 2013). For instance, one strategy to resolve uncertainty about negative outcomes is increased attention to threat-related cues (Bar-Haim et al., 2007). But attention to threat-related cues only serves to further increase estimates of the likelihood of negative outcomes, which further perpetuates feelings of anxiety and the persistence of perceived uncertainty (Grupe and Nitschke, 2013). Another typical anxious behaviour is avoidance of potentially threatening or uncertain situations, but this in turn prevents anxious individuals from being exposed to evidence that might contradict their negative predictions, so they are not resolved (Borkovec et al., 1999). When combined with heightened learning about aversive stimuli and interpretive biases seen in anxiety (Hazlett-Stevens and Borkovec, 2004; Lissek et al., 2005), attempts to resolve uncertainty are often unsuccessful.

We now turn the predictive processing account of anxiety towards two fields of applied research pertinent to anxiety-induced-uncertainty to show how PP can explain previous findings and untangle existing challenges. These fields are: i) fear of falling and altered control of balance, and ii) the breakdown of well-honed motor movements in sport.

4. Motor disruption

4.1. Balance control in the face of uncertainty – fear of falling in older adults

Humans frequently experience disturbances to their postural equilibrium. For example, walking across a slippery or unstable surface, standing on a moving train, or climbing down a set of steep stairs all have the potential to threaten postural stability. Despite this, most people, in most daily situations, will maintain a precise hypothesis (sometimes consciously, sometimes unconsciously) that they will remain stable and not fall.[3] This 'stability hypothesis' is analogous to the general 'healthy body hypothesis' that humans hold, which allows normal variations in somatic symptoms (i.e., sensory noise) to be explained away and major deviations (prediction errors likely to be 'true' symptoms) to be acted on (Ongaro and Kaptchuk, 2019). With respect to balance, failing to hold a 'stability hypothesis' and instead predicting the occurrence of *instability* will (i) ultimately serve to reduce safety because instability will not be treated as an error signal and is thus less likely to be acted on (Russell et al., 2022), and (ii) encourage the individual to avoid most, if not all, activities of daily living. Consequently, most individuals (though not all, see Section 4.1.2) generally expect that they *will* be stable. Instead, what changes is the precision afforded to these prior beliefs about stability, with precision reduced during situations in which certainty decreases, namely when balance is threatened and anxiety/fear about falling is high.[4] Note, we make a clear distinction here between reduced precision afforded to the expectation of stability (e.g., healthy young adults walking on icy ground; such as in Fig. 2B), and a clear shift in the prior towards actually expecting to be unstable (e.g., the right hand side of Fig. 2D). As we will discuss, these two scenarios may have different behavioural consequences.

In instances of heightened uncertainty about whether one can avoid falling, increased precision is instead afforded to incoming sensory information relating to balance. In other words, incoming sensory information is 'up-weighted' and exerts greater influence on perceptions of stability. This has the effect of generating larger precision-weighted prediction errors when sensory inputs signal instability, allowing rapid, reflexive actions to be triggered to counteract the perceived postural disturbance (and thus serving to minimise the error signal). We suggest that this proposal accounts for several key observations in the field of postural control:

1. **Increased conscious balance processing during anxiety.** It is well established that old and young adults alike will direct enhanced attention towards consciously processing their balance when they are anxious and/or fearful about falling (Ellmers et al., 2021; Huffman et al., 2009; Zaback et al., 2016). As noted previously, from a PP perspective, directing attention towards incoming sensory information is believed to increase the influence of such input on perception (i.e., even small prediction errors will ascend to higher levels of the nervous system thus leading to changes in perception). We therefore posit that the direction of conscious attention towards processing input related to balance when anxious reflects a deliberate attempt to reduce uncertainty about postural (in)stability. This could have both beneficial and adverse effects on movement, as described later.
2. **Increased sensory gain and enhanced perception of postural movements when balance is threatened.** Young adults experience increases in sensory (proprioceptive and vestibular) sensitivity when their balance is threatened and anxiety/fear is high (Horslen et al., 2013, 2014; Naranjo et al., 2015, 2016). We suggest that this reflects the nervous system's attempt to increase its sensitivity (and therefore responsiveness) to incoming sensory input and, by virtue, prediction errors. We believe that this increase in the precision assigned to sensory errors accounts for the enhanced perception of postural movement that has been reported in individuals when their balance is threatened (Cleworth et al., 2019; Cleworth and Carpenter, 2016).
3. **Enhanced cortical (error) response to instability during conditions of postural threat.** A stereotyped cortical (EEG) response, termed the N1, occurs 100–200 ms after a loss of balance. This response is hypothesised to represent the cortical processing of sensory prediction errors (Adkin et al., 2006). The N1 cortical response has been shown to be enhanced (by over 80%) in young adults during conditions of increased postural threat when anxiety/fear of falling are high (Adkin et al., 2008). Of particular note, N1 responses were strongly correlated ($r = 0.71$) with the level of balance confidence that participants reported before the trial commenced. In other words, the anxious participants who felt less confident that they could maintain postural stability when their balance was threatened upweighted sensory prediction errors; providing perhaps some of the strongest evidence that increased uncertainty leads to enhanced (cortical) processing of sensory errors.

Combined, we believe that these findings provide strong evidence for

[3] Note, please see subsequent sections for further discussion of the maladaptive outcomes when such highly precise predictions *do* occur.

[4] We therefore argue that the content of 'imprecise' predictions such as "I *should* be stable" or "I *might* be stable" are not inherently different from the precise prediction that "I *will* be stable" – but rather merely represent different (i.e., reduced) levels of precision afforded to the belief that one will be stable.

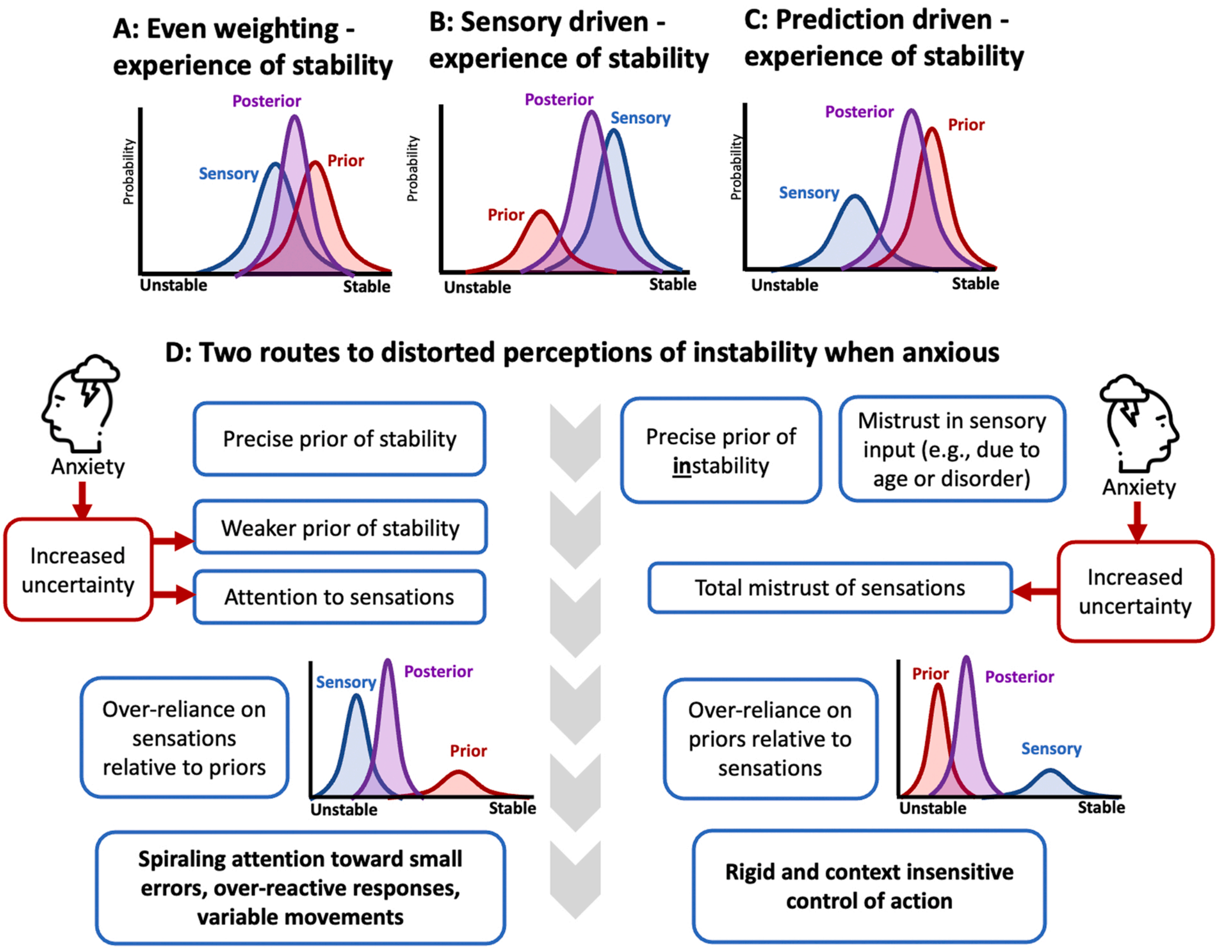

Fig. 2. **A**, **B** and **C** illustrate the principle of precision weighting, where posterior beliefs/perceptions are a joint estimate of expectations and sensory signals, weighted by their estimated precision (width of the distribution), across multiple cortical levels. In **A**, both priors and sensory information favour postural stability and are weighted equally. In **B**, the expectation of postural stability is both lower (and more uncertain) but is overwhelmed by the more precise information that balance is indeed stable. In **C**, the sensory information indicates possible instability, but the stronger prior again leads to the perceived experience of stability. Panel **D** illustrates two ways in which anxiety may disrupt postural control (described in detail in Section 4.1). For individuals who expect to be stable (left) but assign reduced precision to predictions and enhanced attention to bottom-up input when anxious, small (and potentially 'normal') sensory errors will be passed up the cortical hierarchy and perceived. Increased attention to these errors leads to attempts to (over)correct them and a reduced influence of previously strong motor predictions, creating a negative spiral of conscious control and degraded, variable movement. For individuals who expect to be *un*stable, due to for instance previous falls (right), the added uncertainty about sensory input and the environment during anxiety may induce a simplified and rigid movement strategy as an active attempt to deal with this uncertainty. Two similar routes could also explain anxiety-related performance breakdown in sport or other skilled movement tasks (as described in Section 4.2).

an up-weighting of sensory input (and a concomitant reduction in the precision afforded to prior beliefs about stability) during situations of high uncertainty about stability. This has the effect of allowing even small prediction errors to ascend to higher levels of the nervous system, leading to changes in perceptions of stability. In other words, deviations in stability will be perceived more easily, resulting in the triggering of rapid, reflexive actions to counteract the perceived postural disturbance and minimise the error signal.

In contrast, during situations with low uncertainty (e.g., walking in a familiar environment where anxiety/fear about falling is low), only very large prediction errors will be perceived and acted on – given that highly precise beliefs about stability will dominate in such instances. This proposal is supported by work from the domain of psychiatry, which has reported how threat-related anxiety leads to the amplification of sensory prediction errors (and the concomitant reduced precision of prior beliefs) (Cornwell et al., 2017). These authors suggest that such alterations may aid the detection of salient sensory stimuli when threatened.

4.1.1. *The downside of enhanced sensory prediction errors*

When precise priors dominate, small prediction errors are typically disregarded as random noise, and are not passed up through the nervous system. In contrast, up-weighting of sensory input allows for increased influence of small sensory prediction errors, so that minor deviations in postural stability will be perceived and acted upon. However, such up-weighting also increases the risk that minor fluctuations within 'normal' bounds will be perceived as instability. As Edwards et al. (2012) write, "*No sensory system is perfectly noiseless; even in the absence of stimuli there will be random discharges of sensory receptors and neurons. Given sensory data from other sources suggesting the absence of a stimulus, or a prior expectation that no stimulus is present, this noise will be explained as such by the predictive coding scheme and will not be perceived.*" (p. 3502). However, when priors are held with reduced precision and sensory prediction errors are enhanced – such as when anxious/fearful – this increases the likelihood that random noise will be treated as a real stimulus. We argue that this may underpin the distorted perceptions of instability that have been frequently reported to occur in old and young adults who are anxious/fearful about falling (Cleworth et al., 2019; Cleworth and Carpenter, 2016; Ellmers et al., 2021; Huffman et al., 2009). Indeed, there is strong evidence to suggest that such distorted perceptions are driven by increased conscious attention being directed towards monitoring (i.e., 'up-weighting') incoming sensory information pertaining to balance and stability (Ellmers et al., 2021).

Affording greater precision to incoming sensory information will, however, impair movement control in instances where sensory processing is noisy or imprecise, such as is the case for older adults (Konczak et al., 2012). In these instances, up-weighting sensory input will increase the likelihood of *incorrectly* perceiving noise to be a genuine error signal (Wolpe et al., 2016). This will lead to an overestimation of instability and the triggering of excessive and inappropriate motor adaptations to contend with the (incorrectly perceived) error signals (Ayoubi et al., 2015). Thus, rather than up-weighting the stream of noisy sensory input, it would be more appropriate for these individuals to increase the precision of motor predictions (Wolpe et al., 2016) – so long as these predictions themselves are accurate (see below).

4.1.2. Strong priors of instability and a mistrust of sensory information

While most people, in most daily situations, will not predict that they will be so unstable that they will fall, there will be certain individuals who do possess highly precise prior expectations of instability (even in the absence of anxiety). We suggest that this will especially be the case for those individuals who have fallen and who believe they have little control over preventing another fall from occurring (Ellmers et al., 2022). We also posit that precise priors of instability can also arise from excessive precision being afforded to an isolated (and potentially incorrect) percept of instability. For instance, an older person who frequently ruminates about a previous instance in which they felt unstable would unwittingly find this prior afforded enhanced precision by virtue of these ruminations. This is not dissimilar to the hypothesised origin of chronic pain (Ongaro and Kaptchuk, 2019), as well as functional motor and sensory symptoms (Edwards et al., 2012), whereby an initial precipitating event (i.e., symptom) is afforded excessive precision, resulting in an abnormally precise and resistant (non-conscious) prediction of future symptoms.

According to Bayesian principles, highly precise beliefs about instability/propensity for falling will be particularly influential in those with noisier or less precise sensory systems (e.g., older adults). Accordingly, research in ageing has shown increased weighting of prediction models and a down-weighting of sensory input, with these changes corresponding to reductions in sensory sensitivity (Konczak et al., 2012; Moran et al., 2014; Wolpe et al., 2016). It therefore seems highly probable that individuals with less trust in the fidelity of balance-related sensory input (e.g., older adults) will instead rely on prior models to control their posture. Indeed, for older adults protective stepping in response to a physical perturbation appears to be "*not triggered directly by specific sensory input reflecting the state of balance stability but [rather] to involve a pre-selection process […] initiated before it may have actually been needed*" (Rogers and Mille, 2016, p. 4544). This seems to particularly be the case in older adults who have recently fallen; and who are thus more likely to have strong priors about instability in situations that threaten their balance (Batcir et al., 2020). Recent research even highlights how highly precise, yet incorrect, beliefs about upcoming instability can lead to individuals with precise sensory input (i.e., healthy young adults) perceiving imbalance (Castro et al., 2022; Russell et al., 2022), further emphasising the role of prior beliefs in the perception of postural stability.

But what happens when situations of anxiety-related uncertainty are combined with abnormally strong priors (predicting instability) and systemic mistrust for incoming sensory information, as is seen with increasing age? These individuals will (i) predict with high certainty that they will be unstable/fall in situations that they perceive to threaten their balance, and (ii) down-weight (i.e., ignore) any incoming sensory evidence to the contrary (and which would otherwise be used to update perceptions of stability). This then (iii) results in the persistent and inaccurate percept of instability, leading to (iv) the persistence of overly-cautious movement patterns intended to counter the (incorrectly) predicted destabilisation.[5] Indeed, such patterns of behaviour are reliably observed in older adults who have previously fallen (i.e., strong priors of instability) and who are highly anxious/fearful of falling again (Delbaere et al., 2009; Herman et al., 2005; Mille et al., 2013) and who report distorted perceptions of instability (Batcir et al., 2020). However, whilst these movements will be conservative and overly-cautious, they are likely to also be inappropriate for the current context, given that reduced weight is afforded to incoming sensory feedback that would otherwise be used to plan, guide and refine movement in an online manner (Rogers and Mille, 2016). Movements will therefore also be highly prone to large and persistent errors (Rogers and Mille, 2016). This may be one reason why such overly-cautious behaviours are associated with reduced safety and increased falls (Mille et al., 2013; Verghese et al., 2009).

Distorted perceptions of instability may, therefore, have two possible underpinnings. These may be driven by either over-sampling of incoming sensory information (i.e., up-weighting of sensory information and prediction errors) or increased influence of (incorrectly) predicted instability. These causes are, however, hypothesised to affect behaviour in different ways. If distortions are driven by up-weighted sensory prediction errors, then this will result in inappropriate behavioural responses when error signals are (incorrectly) 'detected' (i.e., inappropriate feedback control mechanisms). In contrast, inappropriate predictions will instead result in the rigid maintenance of overly cautious patterns of movement initiated to counter the (incorrectly) predicted instability (i.e., inappropriate feedforward control mechanisms). Preventing individuals from directing conscious attention towards processing incoming sensory information (e.g., through a cognitive distraction task; see Ellmers et al., 2021) may therefore help determine the cause of any observed distortions in perceived stability. For example, if distorted perceptions persist when conscious processing of sensory input is prevented, then it is likely that these are instead a consequence of inappropriate, highly precise predictions (rather than inappropriately high precision afforded to sensory input).

4.1.3. Risky business: Inappropriate predictions of stability

Whilst inappropriately strong predictions of instability and falling can have negative consequences, as described above, overconfidence pertaining to perceived stability can be equally detrimental. Delbaere et al. (2010) reported that around 20% of older adults will over-estimate their balance capabilities, with these individuals failing to safely adapt their balance in response to the task demands (Butler et al., 2015; Sakurai et al., 2013). Such 'risk-taking' behaviours have been shown to predict future falls, even when controlling for other known risk factors (Butler et al., 2015).

As ageing is associated with an increased weighting of sensory prediction models and a down-weighting of sensory information (Wolpe et al., 2016), during situations of increased uncertainty, older adults who predict with high precision that they will be stable/avoid falling will see these beliefs exert a particularly strong influence over perception and movement (much like the previously described precise predictions of *in*stability). If these precise predictions are overly confident, and fail to reflect an individual's *actual* balance capability, then: (i) any

[5] We contend that these cautious behaviours will typically be initiated and controlled via conscious, cortical circuits (Ellmers et al., 2021), but the resultant sensory feedback will not be consciously processed, per se (as to do so would increase the precision afforded to incoming sensory information and, by virtue, the influence of sensory prediction errors).

incoming sensory evidence that challenges this prediction (i.e., information that would inform them that they are in fact unstable) will be afforded low weight and ultimately disregarded, leading to (ii) the persistence of inappropriately risky behaviour unmatched to, and thus failing to reduce, any instability experienced.

4.2. Amplified bottom-up signalling and the breakdown of expert skills – 'choking' in sport

PP generates a particular view of motor expertise, where expert abilities are construed entirely as more accurate prediction making about the bodily or worldly environment (Cappuccio et al., 2020; Hipólito et al., 2021). In other words, expert athletes are experts because they are better able to generate highly precise predictions about both the sensory consequences of their movements (allowing for finely-tuned movements to be 'realised'), as well as the environments in which these are performed. This means a model of the world that is more accurate, more sensitive to current context, more attuned to available information, and better for making decisions. Yet, when these previously precise (motor) predictions become uncertain, athletes may experience a 'choke'.

A choke is a temporary inability to produce routine, habitualised actions in a familiar sensorimotor context. More broadly, choking is commonly defined as, 'performance decrements under pressure situations' (Baumeister, 1984, p. 610), despite striving for superior performance. The choke is not a random fluctuation in performance but a specific negative response to perceived pressure (Hill et al., 2010a; Hill et al., 2010b). As a result, skills that have been refined with practice can breakdown just when the desire to execute them is greatest. Factors that increase the importance of performing well (i.e., performance pressure; Baumeister, 1984) often result in the experience of anxiety. Anxiety subsequently has negative effects on motor skill performance (Nieuwenhuys and Oudejans, 2012; Vine et al., 2016).

As discussed, anxiety is a state of generalised uncertainty which leads to the down-weighting of previously precise predictions, and faster but relatively indiscriminate responding under threat (Lawson et al., 2021). While down-weighting predictions to learn more quickly may be useful in situations of real threat (e.g., when one's life is in danger), in high-pressure sport where expert performers must rely on their super-prediction abilities, such down-weighting is most likely maladaptive. Less precise predictions leave room for more variable motor outputs, as increased precision afforded to incoming sensory input increases the likelihood of the performer attempting to correct perceived errors in an online manner. Further, the failed attempts to skilfully regulate action generates prediction error signals which indicate that the predictive model is currently poor. To rectify poor movement, sensory signals and attention to one's own movements are further upweighted, creating a feedback loop that erodes trust in one's expert sensorimotor predictions (Cappuccio et al., 2020). In situations of pressure, the cost of errors is also greater (i.e., higher pragmatic value of actions), so small deviations in skill execution will be viewed as significant deviations rather than noise in the system, which will further contribute to the negative cycle of error up-weighting. This effect may be further enhanced by a generalised increase in error monitoring during anxiety (Moser et al., 2013). This type of feedback loop is consistent with observations in sport that initial failures generate a negative spiral of errors (Harris et al., 2019, 2021), and the converse for peak states like flow (Jackson, 1995).

At its most extreme, excessively attending to the sensory consequences of action could conceivably preclude movement altogether, given that such deployment of attention will boost, rather than suppress, the counterfactual prediction that no movement has been initiated (Brown et al., 2013). As such, the descending predictions of the intended proprioceptive state are afforded reduced precision, and no movement ensues. This may explain why many expert athletes describe freezing and being unable to initiate movement altogether during pressurised situations; a phenomenon often referred to as being "paralysed by anxiety" (Williams and Wigmore, 2020).

Similar processes may also be at play for another type of 'action', the control of eye movements. Choking frequently occurs during discrete, time-pressured 'aiming' tasks, such as taking a penalty kick, making a golf-putt or throwing a basketball free-throw (Wilson et al., 2009). In such tasks, effective performance is consistently characterised by what is referred to as the 'quiet eye' (Vickers, 2007): a final task-relevant fixation lasting a minimum of 100 ms that directly precedes movement initiation. Research has demonstrated how anxiety can disrupt the quiet eye in a range of motor tasks (Vine et al., 2013), leading to reductions in performance. Such breakdowns in visuomotor control could be explained through the model we have described: the performer is less confident about their predictions and so attempts to reduce such uncertainty by 'over-sampling' from their environment. Control of the oculomotor system to direct foveal vision can be thought of as a series of experiments for attaining information about the world, guided by a set of hypotheses (the generative model) (Friston et al., 2012a). In essence, we should use fixations to resolve uncertainty, such as fixating the bounce point of a moving ball to determine its future trajectory (Diaz et al., 2013; Land and McLeod, 2000). When the world seems uncertain, vision will be deployed to try to resolve this uncertainty, which could manifest as an increased sampling of the world, such as more numerous fixations (of shorter duration) directed to more locations in the environment. This kind of increased visual sampling has been observed in many sporting tasks, and depicted as an 'inefficient' use of visual attention that contributes to choking (Janelle, 2002; Williams et al., 2002; Wilson et al., 2006).[6]

The skill acquisition literature has focused heavily on debates between two explanations of choking: distraction based theories and explicit monitoring theories (Payne et al., 2018; Roberts et al., 2017). *Distraction theories*, such as attentional control theory (ACT) and attentional control theory sport (ACTS) (Eysenck et al., 2007; Eysenck and Wilson, 2016), propose that pressure-induced-anxiety directs resources away from the task and towards irrelevant or threatening information (e.g., worries or opponents) (Beilock and Carr, 2005; Lee and Grafton, 2015; Wilson, 2008). This shift is associated with a reduced influence of goal-directed attentional control and an increase in stimulus driven attention (e.g., hypervigilance to threat) (Eysenck et al., 2007). By contrast, *explicit monitoring theories,* such as reinvestment theory (Masters and Maxwell, 2008), suggest that pressure actually *increases* the amount of attention directed to the task, but that this attention can have adverse effects when it leads to conscious control of previously automated motor programs (Beilock and Carr, 2001; Masters and Maxwell, 2008). When considered in light of PP descriptions of attention, as precision-weighting of prediction errors, these two explanations are easily reconciled (e.g., see Cappuccio et al., 2020).

The description of choking as attentional upweighting of sensory channels clearly fits neatly with self-focus type effects; upweighted sensory errors is a very similar description to explicit monitoring. But the same attentional mechanism may also be at play for distraction type effects. As discussed, expert execution of well learned skills requires attentional facilitation of top-down predictions of proprioceptive input (Brown et al., 2011). Consequently, distraction – in the form of worry or attention to task-irrelevant stimuli – that down-weights this goal-directed facilitation of motor predictions should also be detrimental to motor performance. Motor outputs will be less precise and more prone to failures without the right amount of attentional resource to weight motor predictions appropriately. In short, self-focus and distraction theories can both be subsumed under PP as a form of maladaptive precision modulation that leads to a maladaptive balance

[6] Although opposite effects have also been observed on search rate, which were proposed as a results of a reduction in processing efficiency (Nieuwenhuys et al., 2008).

between predictions and prediction error signalling.

In addition, the principle of precision modulation could account for many of the findings in the choking literature, such as:

1. **Experts choke more** because highly developed motor skills that depend on precise prediction making are more susceptible to disruption when sensory input is afforded greater precision (Gray, 2004).
2. **Responses to anxiety are highly individualised and not all athletes choke at the same time.** Not only is the PP account consistent with transactional approaches to stress that emphasise the appraisal of the threat (Lazarus and Folkman, 1984), but it highlights the importance of the individual's generative model (including prior beliefs) and how it shapes responses to incoming information.
3. **Anxiety can be facilitative.** Upweighting of sensory information in uncertain environments is potentially facilitative for rapid responding and learning. While we have focused on breakdowns, this PP account also describes how increased attention to prediction errors can be useful, as long as it does not become excessive.
4. **Both distraction and self-focus effects can disrupt performance.** As discussed, the precision modulation mechanism can apply to both an underweighting of predictions when attention is misallocated, as well as the spiral of negative outcomes and increased movement monitoring when too much is allocated to sensory signals.

The PP approach also suggests some additional intervening or contributory factors which could moderate this relationship between anxiety-induced uncertainty and motor breakdowns. For instance, reinvestment tendencies (Masters et al., 1993) where individuals have a propensity to over-attend to movement will likely exacerbate the already maladaptive precision modulation occurring during anxiety (Cappuccio et al., 2020). Confidence or self-efficacy is likely to have the opposite effect and enhance the use of predictions, which would mitigate against pressure. The importance of confidence for mitigating against anxiety has already been demonstrated in sport (Besharat and Pourbohlool, 2011), and individuals have been shown to estimate their confidence in their predictions in accordance with Bayes-optimal statistics (Heilbron and Meyniel, 2019).

In summary, there is considerable potential for using PP to understand choking in sport. As well as bringing together self-focus and distraction accounts, a PP approach can generate testable predictions about the mechanisms behind choking. For instance, we should observe motor actions and eye movements that are less prediction-driven under anxiety, leading to more variable outputs. We should also see faster belief updating (i.e., higher learning rates), increased prediction error signalling, and responses that are more biased towards recent observations. This theoretically driven approach could help to move choking research on from traditional debates about self-focus and distraction and towards answering new questions.

5. Next steps: testing this account

The ease with which the PPF (Clark, 2013b; Hohwy, 2020; Seth, 2015), and in particular active inference (Brown et al., 2011; Friston et al., 2010; Parr and Friston, 2019), can account for anxiety-induced disruptions to motor control across seemingly disparate areas such as balance in older adults and sporting expertise speaks to its potential utility. Situating our understanding of anxiety within a wider theoretical framework of perception and action may also be useful for generating and testing new hypotheses and advancing our understanding of underlying mechanisms (e.g., the shifting balance between priors and online sensory information). It may also help untangle some conceptual problems such as self-focus versus distraction theories of choking. This understanding can in turn support the design of interventions. In the case of falling, for example, understanding how rigid expectations of instability interact with attenuated proprioceptive feedback about the current state of the body will help interventions designed to redress this balance (see next section).

Before these benefits can be realised, however, direct testing of the credentials of this approach is needed. A number of testable hypotheses arise from a PP approach to anxiety-induced motor disruption. For instance, if anxiety is indeed an expectation of uncertainty held with low precision (Clark et al., 2018), we would expect agents to actively seek to resolve uncertainty using motor movements. This could manifest as, for example, fixations and saccades towards areas of the visual scene that are not directly goal-relevant but which are deployed to actively resolve the perceived uncertainty (Friston et al., 2012a).

A clear prediction of active inference is that updates to a generative model should be accelerated in situations of uncertainty or when priors are afforded reduced precision (Behrens et al., 2007; Friston et al., 2016). Previously established motor predictions may, then, be revised more quickly under anxiety, resulting in faster trial-to-trial adjustments. This prediction can be easily tested during both sporting and balance tasks that have established predictive movement components. An example is the well-established 'broken escalator' paradigm (Bronstein et al., 2009), in which a brief period of walking onto a platform previously experienced as moving results in a strong stumble-like response (i.e., an inappropriate prediction that the platform will still move). Exploring the rate at which this faulty response is updated would provide insight into the extent to which an individual relies on priors versus bottom-up sensory input to control balance. Indeed, slow rates of updating in this paradigm have been reported in patient groups hypothesised to rely excessively on (inaccurate) priors to regulate movement (Lin et al., 2020). The application of computational modelling approaches to describe this updating of actions over successive trials (e.g., as in Arthur and Harris, 2021; Harris et al., 2022) can also be used to infer the generative processes (e.g., strength of priors and learning rates) that underpin active inference and therefore test these hypotheses about anxiety. Initial application of a modelling approach has shown that updating of motor predictions may be impaired under anxiety due to perceived uncertainty about outcome rewards (Sporn et al., 2020), although state anxiety may actually bias estimations of volatility more than outcome uncertainty (Hein et al., 2021). Similarly, the use of EEG markers of prediction error signalling under anxiety (Hein and Herrojo Ruiz, 2022) can be further used test whether prediction errors related to motor adjustments are atypical during anxious states.

Finally, it may be informative to examine verbal reports of confidence in motor movements, particularly for applications to disrupted balance in older adults where distorted expectations of stability are a known problem (Ellmers et al., 2021). A meta-cognitive belief in uncertainty should lead to reduced confidence in verbally reported predictions (Yon and Frith, 2021). It is also well-established that anxiety induces a more conscious mode of action control (Ellmers et al., 2021; Masters and Maxwell, 2008). We expect that this would hold for predictions about motor movements under anxiety and, if consciously accessible, would provide a way to test whether people are aware of reduced precision in their expectations of movement outcomes.

6. Practical recommendations

What implications does this understanding of disrupted gait and falls and choking have for those working in applied motor control areas? Broadly speaking, practical interventions should be directed at restoring a more adaptive balance of predictions and sensitivity to sensory prediction errors, and at helping these to be appropriately adapted to the current context. Based on the aforementioned predictive processing account of falls and fear of falling we hypothesise that negative outcomes will occur when individuals:

- *Excessively* up-weight the influence of sensory prediction errors during situations of uncertainty, particularly if sensory input is increasingly noisy or imprecise (as often is the case in older adults).

- Adopt highly precise – yet incorrect – predictions about movement capability (i.e., over- or under-estimated stability/risk of falling).
- Utilise overly rigid and simplified movement strategies, while ignoring sensory feedback that could help to better regulate movement.

Therefore, it is crucial that older adults are able to accurately predict their postural stability in a range of contexts and tasks and do not over- or under-estimate their balance capabilities. For instance, preliminary research suggests that novel technologies such as exergaming and neurofeedback may be effective in recalibrating older adults' predictions and judgements relating to their postural stability (Ellmers et al., 2018). Relatedly, recent pilot work has shown that providing individuals with objective data pertaining to their balance performance (a video recording and postural sway data recorded from a force platform) may also be an effective way of challenging persistent incorrect priors of instability (Murillo et al., 2022). Alternatively, if maladaptive priors are maintained through ruminations about previous instances of instability (as described in Section 4.1.2), then clinicians could look to directly target these cognitions through psychotherapy (e.g., rumination-specific CBT (Watkins et al., 2011)).

For both athletes placing excessive precision on bottom-up sensory information, there are two broad options: (i) attenuating the influence of proprioceptive sensory signals; or (ii) increasing confidence in top-down predictions. For (i), anxiolytic drugs that block neurotransmitters are an evidence based, but perhaps impractical, solution (Cornwell et al., 2017; Lawson et al., 2021). Instead, methods to distract individuals from overly focusing on movements, or, better yet, supporting an external or goal-directed focus (Wulf, 2013) will likely reduce the attention directed towards the sensory consequences of movement and readdress the balance of top-down and bottom-up signalling. For (ii), appropriate methods to increase confidence or self-efficacy (Callow et al., 2001; Short and Ross-Stewart, 2008), or challenge appraisals of anxious symptoms (Moore et al., 2015; Sammy et al., 2017) would seem beneficial. A traditional sport psychology intervention, the pre-performance routine, may be particularly useful for supporting motor predictions. Routines generate familiarity and replicable patterns with known sensory effects can help to reduce surprise and reinforce predictions. The act of fidgeting, a similar non-goal-directed action, has recently been described as performing a 'self-evidencing' function to resolve uncertainty about the world, through simple and precise actions that confirm an agent's self-model (Perrykkad and Hohwy, 2020). We also propose that pre-performance imagery – a technique frequently used by athletes to reduce the likelihood of choking (Hill et al., 2010a; Hill et al., 2010b) – may be similarly effective at enhancing the precision of motor predictions Table 1.

The active inference approach to motor control also has interesting implications for motor learning and skill development. While performers should rely on their previously developed predictions in competition, when trying to modify a skill the additional variability that is encouraged by upweighting sensory feedback through skill focus generates useful variability that can allow new motor patterns to develop (Toner and Moran, 2014). In essence, weaker priors leads to faster learning (Behrens et al., 2007). Findings suggest that anxiety is, however, still detrimental in this context, as learners try to cope with the high degree of uncertainty during early motor learning by constraining their movements into rigid and stereotyped patterns which subsequently prevent skill development (Hein et al., 2021).

7. Conclusions

The present work provides an initial outline of a PP account of motor skill breakdown under anxiety (Clark, 2013b; Hohwy, 2020; Parr and Friston, 2019). The PPF, and related active inference approaches, are increasingly influential neuroscientific theories that are being applied across domains including clinical disorders (Jeganathan and Breakspear, 2021), action observation (Donnarumma et al., 2017), attention (Brown et al., 2011), and motor control (Adams et al., 2013). Active inference is particularly appealing for skill acquisition research as it derived from dynamical systems theory and goes some way to uniting traditional cognitivist approaches with a growing interest in enactive and embodied approaches to perception and action (Bruineberg and Rietveld, 2014; Constant et al., 2021).

Table 1
glossary of terminology.

Counterfactual prediction	Predictions of sensations that have not yet happened.
Sensory prediction errors	The deviation between predicted and received sensory input.
Prior	A probabilistic belief about a hidden state or parameter.
Posterior	A joint estimate comprised of the prior and some newly observed information.
Precision	The reliability assigned to a piece of information that scales its weighting in subsequent computations – formally, the reciprocal of the variance of its probability distribution.
Precision weighted prediction error	The error signal passed up the cortical hierarchy resulting from the size of the prediction error, scaled by a precision weighting factor.

We have suggested that the PP conceptualization of anxiety as a state of uncertainty explains common observations of spiralling skill-focused attention and movement monitoring via changes in precision weighting of predictions and sensory prediction errors. The result is movement that is *too reactive* and devoid of normal predictive guidance. Further to this, active attempts to counteract intolerable levels of uncertainty (such as in older adults with fear of falling), can conversely lead to movement control that is overly rigid or simplified (Arthur and Harris, 2021; Delbaere et al., 2009; Sporn et al., 2020).

Whilst the specific hypotheses described require further empirical testing, there are reasons to believe that the framework presented herein has much to offer. Not only does it address the significant challenge of accounting for individualised responses to anxiety, which are often negative but can sometimes also be adaptive; but it also explains different (and often contrasting) routes to two types of motor disruption. We have also suggested it is able to unify existing accounts of choking in elite sport, as well as explain a common problem of much applied significance (disrupted gait and falls in older adults). Therefore, there is significant potential for a PP account of motor disruption to guide future work and provide a unified and principled account of motor disruption.

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Declarations of interest

None

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