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Mechanisms for handling uncertainty in sensorimotor control in sports: a scoping review

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ABSTRACT

In complex naturalistic sensorimotor behaviour, uncertainty arises from ambiguities and delays in sensory inputs as well as noise in sensory detection and motor execution. In sports, where human capacity reaches its limits, handling uncertainty is crucial. In fundamental motor-control research, five mechanisms for handling uncertainty – multisensory integration, prior-knowledge integration, risk optimisation, redundancy exploitation, and impedance control – have been proposed based on a rich body of evidence, mostly investigating simple arm and hand movement tasks. Here we review the literature investigating more complex tasks and examine to what extent these mechanisms explain handling uncertainty in sensorimotor control in sports. A systematic search following the PRISMA guidelines resulted in the consideration of 82 studies. These studies provide robust empirical evidence for the mechanisms of multisensory integration, prior-knowledge integration, and redundancy exploitation in complex naturalistic behaviour, whilst only a few publications focused on the other two mechanisms. Furthermore, only a few studies test model-based predictions that can be derived from the theoretical frameworks to a satisfactory extent. Finally, beyond discussing these explanatory mechanisms in isolation, we propose a unifying model that builds upon the theory of optimal feedback control, in which the mechanisms can be related to each other coherently.

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Uncertainty; noise; sensorimotor control; optimal feedback control; Bayesian inference; sport

1. Introduction

Our world is riddled with uncertainty. In sports, for instance, when a climber jumps to a hold she has never touched before, a number of – maybe vital – questions arise. How far is the jump and how big is the swing that has to be absorbed? How good is the hold in terms of shape and friction? Where exactly is the sweet spot of the hold? What is the optimal sequencing of subsequent actions and what is the optimal timing for this sequence? What are the consequences of a fall? In such cases of natural sensorimotor behaviour, uncertainties like these arise from different sources; particularly from ambiguities in the sensed environment (e.g. Kersten et al., 2004; Witt & Riley, 2014) as well as from

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noise in sensory and motor systems (e.g. Faisal et al., 2008; Körding & Wolpert, 2006). Moreover, we have to handle sensory-input delays and typically, the multiple possible solutions to solve a motor task (e.g. Franklin & Wolpert, 2011).

When relating these considerations for behavioural control to probabilities, uncertainty can be defined as 'possible states or outcomes measured by assigning probabilities to each possible state or outcome' (Sternad, 2018, p. 184). This definition can be further specified by the differentiation between expected and unexpected uncertainty and volatility (Bland & Schaefer, 2012). Expected uncertainty regards cases when the outcome probabilities are known and stable, like the outcome uncertainty of rolling a six from a dice. Unexpected uncertainty would occur if the dice was suddenly changed to a cheat dice with unusual probabilities, whose probabilities can no longer be predicted by past experience. Finally, volatility means a frequent change in probabilities, for example, due to a frequent change over several cheat dice.

In sports, where human capacities are characteristically brought to their limits, successfully handling different types of uncertainty is crucial. Thus, the question arises of how humans are able to master this challenge. In fundamental sensorimotor-control research, a rich body of evidence has been provided for five mechanisms contributing to the scientific explanation of how humans handle uncertainty in behavioural control (for reviews, e.g. Franklin & Wolpert, 2011; Gallivan et al., 2018; Körding & Wolpert, 2006; Todorov, 2004):

(1) *Multisensory integration*

In order to reduce sensory ambiguity and to obtain a more robust state estimate, information from different sensory modalities can be combined and weighted according to their relative reliability; as commonly approached by the principles of Bayesian statistics (Ernst & Banks, 2002).

(2) *Prior-knowledge integration*

Similar to integrating different sensory inputs, uncertainties about the current state can be reduced by integrating current sensory information and existing prior knowledge according to Bayesian principles (Körding & Wolpert, 2004).

(3) *Risk optimisation*

As real-world tasks typically exhibit motor equivalence, meaning that many possible movement variants exist to solve a given task, it is valuable to estimate the uncertainty connected to these movement variants to consider the associated risks. To obtain an optimal trade-off between outcome-related costs and rewards, inherent motor noise should be taken into account in motor planning and control (Trommershäuser et al., 2003).

(4) *Redundancy exploitation*

Behavioural control can be conceptualized as searching for an optimal variant in a redundant task-solution space. This implies that uncertainty due to motor noise only needs to be minimized if goal-relevant variables vary beyond the range of optimal solutions – an idea that can be traced back to Bernstein (1987) and has been formulated thereafter in the uncontrolled-manifold hypothesis (Scholz & Schöner, 1999) or the principle of minimal intervention (Todorov & Jordan, 2002).

(5) *Impedance control*

As an alternative to actively handling noise-related uncertainty, robust motor-task solutions can also be achieved by adapting one's resistance to expected uncertainty. Specifically, by co-contracting muscles and thereby increasing muscle stiffness and impedance to respond to an expected range of perturbations, unexpected perturbations within the expected intensity range are immediately dampened (Burdet et al., 2001; Hogan, 1984).

Since the five reported mechanisms are drawn from foundational motor-control research, most of which examines simple pointing or reaching movements, the question arises whether or to what extent the same mechanisms hold for the handling of sensorimotor uncertainty in more complex real-world situations, as are common in sports. The main goal of this review is therefore to investigate the external validity of these mechanisms. On the one hand, there is no reason to necessarily doubt this, but on the other hand, the external validity of basic research results cannot be taken for granted (see, e.g. Wolpert et al. (2011, p. 748) in their review on computational mechanisms of human motor learning: 'It is not clear whether the learning models that are developed will generalize to tasks such as tying shoelaces or learning to skateboard.'). Hence, it seems extremely valuable for both sports scientists and practitioners to take a closer look at exactly this question in order to gain a well-grounded knowledge base for handling uncertainty in complex, in particular sports-related tasks. Furthermore, the present review can claim relevance for contexts beyond sports, such as questions of complex sensorimotor control in professional fields or traffic.

In a recent narrative review, Gredin et al. (2020b) propose a Bayesian framework to explain anticipatory behaviour in sports. They summarize multiple studies with overall good evidence in favour of the integration of contextual information into perception. The authors conclude that athletes reduce perceptual uncertainty by weighting different contextual and kinematic information sources according to their reliability and, by this means, enhance anticipatory behaviour. However, this conclusion on multisensory integration was drawn from foundational research on pointing and reaching-and-grasping tasks. Furthermore, by focusing on Bayesian inference in anticipation, Gredin et al. (2020b) do not address additional mechanisms for handling uncertainty in complex motor behaviour; namely, risk optimisation, redundancy exploitation, and impedance control.

Therefore, in the present scoping review, we systematically list and discuss all original articles on handling uncertainty in natural sensorimotor, in particular sports-related tasks. This approach not only builds from a narrative to a scoping review, but also extends investigations on anticipatory behaviour to consider control mechanisms beyond Bayesian inference. Furthermore, we substantially broaden the current view by relating our findings to theoretical approaches rooted in either the ecological or the cognitive branch of motor coordination and control theory.

2. Method

This review followed the guidelines of Tricco et al. (2018) for the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews (PRISMA-ScR). The respective checklist can be found in Appendix A.

2.1. Inclusion and exclusion criteria

To be included in the review, the studies had to examine uncertainty aspects related to sensorimotor control in sports. No studies on sensorimotor learning or optimisation were included (e.g. focussing on the optimal degree of fluctuations in practice; Hossner et al., 2016). Moreover, studies on scattering in motion were excluded from the current review if there was no examination of task-relevant or -irrelevant variables (e.g. Den Hartigh et al., 2015). Studies on Fitts' or Hick's law were excluded as they do not address uncertainty at the core (e.g. Sanderson, 1983). Furthermore, no clinical or paediatric studies were considered as the focus was not on impairments or the development of the reviewed mechanisms.

The exclusion criterion for studies 'not related to sensorimotor control in sports' pertained to those which investigated decision-making behaviour with uncertainty, however, did not deploy a sensorimotor task (e.g. Adie et al., 2020). To be considered sports-related and included in the present review, the studies had to meet at least one of the following two conditions: Studies were included that used naturalistic sports-related stimuli (e.g. Gredin et al., 2018; Helm et al., 2020) or required a motor response beyond pointing or reaching-and-grasping movements, i.e. tasks involving whole-body movements such as throwing or catching (e.g. Stevenson et al., 2009). To clarify, if only a simple motor action was requested, but a natural sports-related stimulus was used, the study was still considered, because the complexity of reacting to, for instance, videos of moving persons with a high degree of dynamics in it (even with a button press) seems to be sufficiently close to real-world tasks like pulling the brake at the right moment in downhill biking. However, studies in which no motor response (i.e. exclusively perceptual tasks) was required at all were not included in the review.

Further, only original articles with empirical data published in peer-reviewed journals in English language were included. Finally, it should be noted that the paper of Scott et al. (1997) summarizes the data of several other studies (Berg et al., 1994; Hay, 1988; Hay & Koh, 1988; Lee et al., 1982), which will not be considered separately in the results section.

2.2. Identification and screening

The following six academic databases were searched: PsycINFO, PubMed, ScienceDirect, Scopus, SPORTDiscus and Web of Science. The last search was conducted on July 15, 2023, using all searching fields with the following terms: (uncertainty OR noise) AND (sensor* OR motor) AND control AND sport AND movement. Moreover, the search was filtered (if possible) to English and original articles that have undergone a peer-review process. In the Scopus database, the subject area was further limited to social science or psychology due to many hits from other scientific disciplines (e.g. engineering or

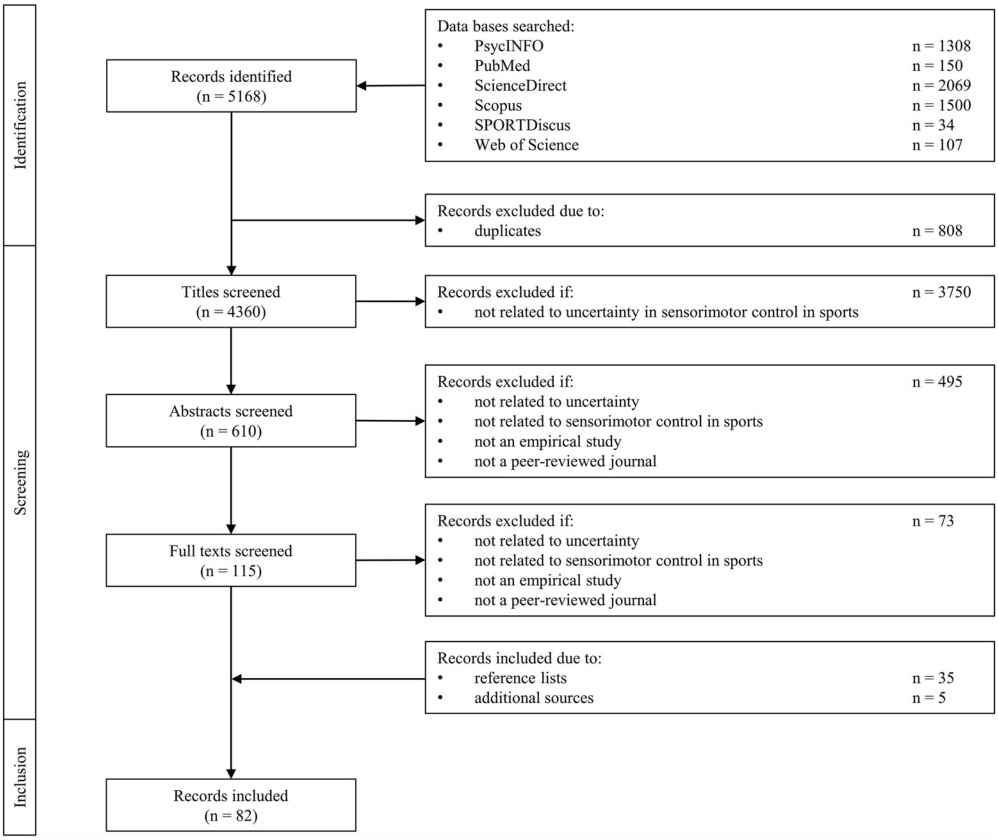

Figure 1. PRISMA flow diagram for the literature search.

computer science). The exact search strategy applied to each database is documented in Appendix B.

As illustrated in Figure 1, a total of 5,168 hits were exported to EndNote. Two raters independently screened all titles and abstracts after removing duplicates. The abstracts were then merged, meaning that the articles remained in the pool for full-text screening if at least one of the two raters judged the abstract as fulfilling the inclusion criteria. Furthermore, in an iterative process, the reference lists of all included studies were systematically screened such that 35 additional articles were included for review. Appendix C contains a table indicating which articles were found in the initial search and which were included from the reference lists. An additional five studies were found by forward citation searches and screening of the reference lists of theoretical articles. In the end, 82 articles were included in the review.

3. Results

The final 82 studies are listed in Table 1. The studies are subdivided into the five core mechanisms addressed: multisensory integration, prior-knowledge integration, risk optimisation, redundancy exploitation, and impedance control (including a sixth residual category of further studies). For each subdivision, the studies are sorted alphabetically

Table 1. Studies on mechanisms for handling uncertainties in sensorimotor control in sports, sorted by mechanism and ordered alphabetically.

Mechanism	#	Author(s)	Sport	Task	Type	Main Findings
Multisensory integration	1	Ankarali et al. (2014)	Juggling	Juggling a virtual ball on a screen with a paddle	N = 18 novices, experimental lab study, within-subject design	Additional haptic feedback enhanced juggling performance.
	2	Cañal-Bruland et al. (2018)	Tennis	Predicting the ball's location in occluded videos of rallies	N = 23 experienced players, experimental lab study, within-subject design	Louder tennis stroke sounds were associated with predictions of farther ball flight distances.
	3	Gray (2009)	Baseball	Batting virtual baseballs in video-based situations	N_1 = 10, N_2 = 16 experts, experimental lab study, within-subject design	Visual feedback was given more weight when incongruent with auditory or tactile feedback.
	4	Heinen et al. (2014)	Trampoline	Vertical jumping in synchronisation with a partner	N = 20 experts, quasi-experimental field study, within-subject design	Jump synchronisation was achieved faster when only visual peripheral information was available than when only auditory information was given. Synchronisation was achieved the fastest when both visual and auditory information was available.
	5	Kennel et al. (2015)	Hurdling	Running as fast as possible with manipulated auditory feedback	N = 20 novices, quasi-experimental field study, within-subject design	Performance degraded with delayed auditory feedback, though it could be compensated in later trials.
	6	Krabben et al. (2018)	Judo	Fighting with and without a blindfold	N = 24 experts, quasi-experimental field study, within-subject design	Impaired vision decreased judo performance.
	7	O'Brien et al. (2020)	Golf	Hitting occluded golf balls with the sonification of the club movement	N = 20 novices, quasi-experimental field study, within-subject design	Sonification of the golf club's speed significantly reduced the variability in the distance from the target and ball location estimation.
	8	O'Brien et al. (2021)	Golf	Hitting golf balls with the sonification of the club movement	N = 40 novices, quasi-experimental field study, between + within-subject design	Online error-based sonification feedback with personalised mean velocity profiles reduced variability in the execution and timing of the swing movement more than auditory guidance.
	9	Petri et al. (2020)	Table tennis	Playing strokes under normal or impaired hearing conditions	N_1 = 15 novices, N_2 = 13 advanced players, quasi-experimental field study, within-subject design	Impaired auditory information did not influence hit quality and subjective effort, neither for novices nor for advanced players.
	10	Santello et al. (2001)	Drop jumps	Conducting jumps from different heights with or without vision	N = 8 novices, experimental lab study, within-subject design	The same force patterns were revealed to absorb the jump with or without vision. However, the landing was less smooth, and there was higher intra-individual variability in the force patterns without vision.
	11	Schaffert et al. (2020)	Rowing	Rowing with a target frequency with normal or masked hearing	N = 20 experts, quasi-experimental field study, within-subject design	The masked auditory information led to an increased deviation of the target stroke frequency.

(*Continued*)

Table 1. Continued.

Mechanism	#	Author(s)	Sport	Task	Type	Main Findings
	12	Sinnett and Kingstone (2010)	Tennis	Anticipating the stroke direction from video and sound	N = 33 novices, experimental lab study, within-subject design	Additional sound of white noise affected accuracy and slowed down the response time.
	13	Sors et al. (2018)	Volleyball	Predicting a serve's length as fast and as accurately as possible	$N_1 = 21$, $N_2 = 21$, $N_3 = 17$ advanced players, experimental lab study, within-subject design	With incongruent auditory and visual stimuli, players' predictions followed the auditory information. Only with auditory information the prediction accuracy was higher than chance.
	14	Sors et al. (2017)	Soccer and Volleyball	Anticipating the speed of occluded penalties and smashes	$N_1 = 18$, $N_2 = 17$ advanced players, experimental lab study, within-subject design	When only auditory information was provided, the response time was shorter than for videos without audio. In videos without audio, participants were better than chance at guessing the ball speed. Visual, in addition to auditory information, did not improve the accuracy of speed estimation.
	15	Takeuchi (1993)	Tennis	Playing tennis under normal or impaired hearing conditions	N = 3 advanced players, explorative field study, within-subject design	The players lost more games with earplugs and were less successful in performing returns.
	16	Zelic et al. (2012)	Juggling	Juggling with vibrotactile or auditory feedback	N = 7 novices, experimental lab study, within-subject design	Jugglers' performance improved with the addition of well-scaled auditory and tactile cues.
Prior-knowledge integration	17	Abernethy et al. (2001)	Squash	Returning serves with occluded vision	N = 12 (6 experts, 6 less-skilled players), quasi-experimental field study (no inferential statistics)	Only the experts could exploit context information about situational probabilities in cases of early occlusion of kinematic information to initiate movements in the appropriate direction better than chance.
	18	Arthur and Harris (2021)	Racket sport	Returning bouncing virtual balls	N = 54 novices, experimental lab study, within-subject design	The recent context was more important in the unexpected uncertainty situation than in the expected volatile environment. The gaze behaviour was in line with the simulated predictions of an optimal Bayes integrator.
	19	Berg and Hughes (2017)	Ball catching	Catching vertically dropped balls of different weights	N = 28 novices, experimental lab study, within-subject design	When the ball's weight was unknown, participants showed relatively constant muscle activations for different weights at a level equivalent to the muscle activation for an intermediate weight in the known weight condition.
	20	Berg and Hughes (2020)	Ball catching	Catching vertically dropped balls of different weights	N = 29 novices, experimental lab study, between + within-subject design	When the ball's weight was unknown, participants showed relatively constant muscle activation with different weights at a level equivalent to the muscle activation for the heaviest weight in the known weight condition.

(*Continued*)

Table 1. Continued.

Mechanism	#	Author(s)	Sport	Task	Type	Main Findings
	21	Crognier and Féry (2005)	Tennis	Conducting volleys with occluded vision	N = 17 experts, quasi-experimental field study, within-subject design	The higher the player's tactical initiative, the higher the accuracy of the opponent's anticipated stroke. Controlling rallies reduced the number of options the opponent had, which increased the likelihood of accurate anticipation.
	22	Eckerle et al. (2012)	Ball catching	Catching vertically dropped balls of different weights	N = 29 novices, experimental lab study, within-subject design	When the ball's weight was unknown, participants showed relatively constant muscle activation with different weights at a level equivalent to the muscle activation for an intermediate weight in the known weight condition.
	23	Farrow and Reid (2012)	Tennis	Predicting the ball's location from videos	N = 29 experts (15 late teens, 14 early teens), experimental lab study, between-subject design	Experts benefitted from situational probability information based on the current game score to decrease their response time. This effect was only found in the older athletes.
	24	Gray (2002)	Baseball	Batting virtual baseballs in video-based situations	N = 6 experienced players, experimental lab study, within-subject design	Prior expectations affected the timing of the baseball swing. A two-state Markov model, which considers the preceding state to predict the current state with fixed transition probabilities, worked well for modelling participants' error prediction.
	25	Gray and Cañal-Bruland (2018)	Baseball	Batting virtual baseballs in video-based situations	N_1 = 20, N_2 = 20 experts, experimental lab study, within-subject design	The contextual information about the probability of a fast/curved ball had a greater impact on the number of successful hits under earlier rather than later occlusion conditions. The number of successful hits was higher when the probabilities of the different throws were not equally distributed.
	26	Gredin et al. (2018)	Soccer	Predicting the outcome of virtual 2:2 counterattacks	N = 31 (16 experts, 15 novices), experimental lab study, between + within-subject design	Experts profited from explicit knowledge about the action tendencies in congruent trials but not from knowledge that had to be acquired implicitly. In incongruent trials, explicit knowledge had a higher negative impact on anticipatory judgments in novices than in experts.
	27	Gredin, Bishop, et al. (2020)	Soccer	Predicting the outcome of virtual 2:2 counterattacks	N = 15 experts, experimental lab study, within-subject design	Explicit contextual prior information improved performance. This effect decreased when the reliability of the kinematic information increased. Only explicit prior knowledge with high reliability enhanced performance when the reliability of the kinematic information was also high.

(*Continued*)

Table 1. Continued.

Mechanism	#	Author(s)	Sport	Task	Type	Main Findings
	28	Gredin, Broadbent, et al. (2020)	Soccer	Predicting the outcome of virtual 2:2 counterattacks	N = 15 experts, experimental lab study, within-subject design	Explicit contextual prior information improved performance. This effect decreased with increased cognitive task load.
	29	Gredin et al. (2019)	Soccer	Predicting the outcome of virtual 2:2 counterattacks	N = 18 experts, experimental lab study, within-subject design	Explicit contextual prior information improved performance. Judgment utility reduced this effect and let the focus switch to the highest reward and the most minor loss.
	30	Gülden-penning et al. (2023)	Basketball	Predicting the direction of virtual passes with or without head-fake	N_1 = 31, N_2 = 32 novices, experimental lab study, within-subject design	Implicit and explicit information about action-outcome probabilities increased the head-fake effect with increasing outcome probability. The tendency to respond in accordance with the player's head direction increased linearly with its outcome probability.
	31	Güldenpenning et al. (2018)	Basketball	Slapping a ball of regular or disguised virtual passes	N = 68 novices, experimental lab study, between-subject design	With a low frequency of disguised passes, the reaction time was shorter, and the deception effect in terms of more errors was higher than when the frequency of disguised passes was high.
	32	Harris et al. (2022)	Racket sport	Returning bouncing virtual balls	N = 44 novices, experimental lab study, within-subject design	A hierarchical Bayesian inference model explained anticipatory eye movements better than a simple associative learning model. Pupillary signalling of surprise was associated with estimates of precision-weighted prediction error and learning rates, however, not with beliefs about the volatility of the bouncing ball.
	33	Helm et al. (2020)	Handball	Deciding whether morphed penalty throws are genuine or disguised	N = 23 novices, experimental lab study, within-subject design	Explicit information about the action preferences affected the classification of genuine and disguised throws. This effect was commensurate with the different degrees of ambiguity. When there was low kinematic uncertainty, the explicit information about action tendencies had no influence.
	34	Jackson et al. (2020)	Soccer	Intercepting an approaching virtual opponent	N = 30 (15 experts, 15 novices), experimental lab study, within-subject design	Explicit probability information regarding prior expectations affected performance, especially when aligned with a faked direction. Deceptive actions got 'super-deceptive' as a confirmation bias. For experts, the negative effects outweighed the positive effects.
	35	Leukel et al. (2012)	Fitness	Conducting drop jumps or landings	N = 10 novices, experimental lab study, within-subject design	The muscle activity differed for the conditions with and without uncertainty in task execution. The possibility for a landing reduced muscle activity because less

(*Continued*)

Table 1. Continued.

Mechanism	#	Author(s)	Sport	Task	Type	Main Findings
						muscle activity is required for a landing than for a drop jump.
	36	Loffing and Hagemann (2014)	Tennis	Anticipating the directions of occluded baseline shots	N = 52 (26 experts, 26 novices), Experimental lab study, between-subject design	Experts outperformed novices, and both groups improved under later occlusion conditions. Experts relied more on the opponents' court position in early occlusion time. Novices showed by tendency the same behaviour but less distinctively.
	37	Loffing et al. (2016)	Tennis	Anticipating the directions of occluded baseline shots	N = 40 (20 experts, 20 novices) experimental lab study, between-subject design	Experts outperformed novices, and both groups improved under later occlusion conditions. The opponent's court position was only relevant in the early stage of the movement but not anymore at the moment of racket-ball contact.
	38	Loffing et al. (2015)	Volleyball	Predicting the type of attack in different contexts	N = 51 (20 experts, 31 novices), experimental lab study, between-subject design	Both groups expected a continuation of the currently played pattern. The prediction accuracy was higher in congruent trials, and the response time was shorter than in incongruent trials. The congruence effect was slightly higher for experts than for novices.
	39	Magnaguagno and Hossner (2020)	Handball	Acting as a central defender in virtual video-based situations	N = 24 (12 experts, 12 near experts), experimental lab study, between/within-subject design	All players improved in terms of explicit reports of their teammates' defensive quality and the correctness of their movements. Experts outperformed near experts in all aspects and benefited from a superior self-generated, implicit knowledge base.
	40	Magnaguagno et al. (2022)	Handball	Acting as a central defender in virtual video-based situations	N = 57 (30 youth elite, 27 youth near-elite players), experimental lab study, between-subject design	Providing explicit information improved performance in congruent but impaired performance in incongruent trials. This effect of providing explicit knowledge diminished over time due to the accumulation of implicit knowledge.
	41	Mann et al. (2014)	Handball	Predicting the direction of virtual handball throws	N = 20 experts, experimental lab study, between-subject design	Implicitly learned priors helped to improve the goalkeeper's chance to save the ball in congruent trials but decreased performance in incongruent trials.
	42	McIntyre et al. (2001)	Ball catching	Catching balls on Earth or in space	N = 4 novices, explorative field study, within-subject design	The peak muscle activation was earlier in space than on Earth according to the time of contact with the ball, meaning that the lack of gravity could not be fully adjusted.

(*Continued*)

Table 1. Continued.

Mechanism	#	Author(s)	Sport	Task	Type	Main Findings
	43	Milazzo et al. (2016)	Karate	Reacting to fighting attacks	N = 28 (14 experts, 14 novices), quasi-experimental field study, between-subject design	Only experts enhanced their performance in terms of faster and more accurate responses from the implicitly acquired context regarding repeated attacks every four actions.
	44	Misirlisoy and Haggard (2014)	Soccer	Saving penalties	N = 361 penalties (FIFA World Cups, UEFA Euro Cups), explorative field study	Goalkeepers showed a pattern of a gambler's fallacy by choosing the left or right side, which is not optimal because the kickers showed a pattern close to randomness.
	45	Murphy et al. (2016)	Tennis	Predicting the ball's location in normal and animated videos	N = 36 (16 experts, 20 novices), experimental lab study, between-subject design	When provided only with contextual information and no postural information about the opponent, experts and novices were able to anticipate shots better than by chance. Both groups performed better with the addition of the opponent's postural information.
	46	Murphy et al. (2018)	Tennis	Predicting the ball's location in animated videos	N_1 = 24, N_2 = 24 (12 experts, 12 novices), experimental lab study, between-subject design	Contextual information related to the opponent was weighted more than contextual information related to the ball. However, players integrated all available information sources when making decisions.
	47	Navia et al. (2013)	Soccer	Saving penalties	N = 9 novices, quasi-experimental field study, within-subject design	Explicit situational information about a player's action preference improved the chance for goalkeepers to choose the right corner.
	48	Nakamoto et al. (2022)	Baseball	Batting virtual baseballs in video-based situations	N = 13 experts, experimental lab study, within-subject design	Explicit estimations of ball speed were affected by the speed of the pitcher's movement, especially in conditions with high ball speed and thus less reliable ball flight information. In tendency, this effect was more pronounced for higher-skilled batters.
	49	Runswick et al. (2018)	Cricket	Predicting the ball's location in occluded videos	N = 36 (18 experts, 18 novices), experimental lab study, between-subject design	Both pre-release/contextual information and post-release/kinematic information were considered for anticipation. While the importance of post-release/kinematic information increased over time, the importance of pre-release/contextual information decreased.
	50	Sinn et al. (2023)	Ball catching	Catching vertically dropped balls of different weights	N = 37 novices, experimental lab study, within-subject design	Due to a relatively constant intermediate muscle activation for variable unknown ball weights, catching errors with the lightest ball were characterised by higher and with the heaviest ball by lower reflexive compensatory muscle activation.

(*Continued*)

Table 1. Continued.

Mechanism	#	Author(s)	Sport	Task	Type	Main Findings
	51	Stevenson et al. (2009)	Surfing simulation	Balancing on a board and steering a cursor as close as possible to a target	N = 10 novices, experimental lab study, within-subject design	Subjects steered the movements slower and with less amplitude under increased feedback uncertainty conditions, implying that under greater uncertainty, the human control system integrates information over a longer period.
	52	Triolet et al. (2013)	Tennis	Initiating strokes in ATP tennis matches	N = 3000 strokes by N = 10 experts, explorative field study	Under unfavourable conditions, players initiated their movements earlier and with less response accuracy. When the movement was initiated later than 140 ms after ball contact, the movement almost always went in the right direction.
	53	Wang et al. (2019)	Soccer	Predicting the direction of penalties	N = 50 (25 experts, 25 novices), experimental lab study, between + within-subject design	Prior cues affected the response accuracy of experts and novices in congruent situations positively and in incongruent situations negatively.
	54	Whittier et al. (2022)	Step	Moving the centre of mass to a virtual target	N = 57 novices, experimental lab study, within-subject design	As incoming visual information became less reliable, more weight was given to previously learned body positions as prior knowledge. The position of the centre of mass was estimated consistent with Bayesian inference approaches.
	55	Yamamoto et al. (2019)	Tennis	Estimating the variance of one's own serves	N = 31 (experts and novices), experimental lab study, between + within-subject design	A large isotropic bias was found regardless of experience level, so the estimated eccentricity was lower than observed. No effects of the intervention were revealed.
	56	Zago et al. (2004)	Ball punching	Punching real or virtual falling balls	N = 20 novices, experimental lab study, within-subject design	An integrated prior was found that gravity accelerates the falling ball, even when the virtual ball was not accelerated. This effect decreased with training.
Risk optimisation	57	Bertucco et al. (2020)	Snowboard	Balancing on a rocker board and controlling a virtual snowboard	N = 15 novices, experimental lab study, within-subject design	When the sensitivity of the rocker board was higher, participants chose a safer path by accepting smaller accelerations to reduce the risk of additional penalty points, meaning that participants considered different cost functions according to execution noise.
Redundancy exploitation	58	Bardy and Laurent (1998)	Gymnastics	Conducting somersaults	N = 5 (3 experts, 2 advanced), quasi-experimental field study, within-subject design	Without vision, experts showed a stable, gradually increasing variance of body orientation. Whilst under normal vision conditions, there was a variance increase in the first part of the somersault; experts showed a

(*Continued*)

Table 1. Continued.

Mechanism	#	Author(s)	Sport	Task	Type	Main Findings
						decrease in the second part, i.e. the crucial movement phase for approaching the floor.
	59	Betzler et al. (2014)	Golf	Conducting strokes at a target	N = 285 (all expertise levels), explorative field study, between + within-subject design	Expertise corresponded to a reduction of variance in several (e.g., club head speed, path angle) but not all variables.
	60	Bootsma and van Wieringen (1990)	Table tennis	Conducting forehand drives as fast and accurately as possible	N = 5 experts, explorative field study, within-subject design	The variance of the timing and direction of the initial movement of the bat was higher than for the moment of ball-bat contact.
	61	Burgess-Limerick et al. (1991)	Field hockey	Conducting hockey drives	N = 7 (4 experts, 3 novices), explorative field study, between-subject design	Novices showed less backswing variance than experts but more downswing variance.
	62	Davids et al. (1999)	Volleyball	Serving volleyballs as hard and accurately as possible	N = 6 experts, explorative field study, between-subject design	Experts stabilised the vertical position of the ball at the zenith and contact with the ball but allowed variability in the x-y plane, which they could compensate for.
	63	Dupuy et al. (2000)	Ball throwing	Throwing balls at a target on the floor	N = 8 novices, experimental lab study, within-subject design	The observed angle-speed combinations were close to the mechanical optimum to reduce variance in the throwing distance.
	64	Franks et al. (1985)	Hockey	Conducting hockey drives	N = 1 expert, explorative field study, within-subject design	High variance in the initiation of the stroke was found (i.e. preparation and backswing), but a consistent and accurate downswing.
	65	Hiley et al. (2013)	Gymnastics	Performing giant circles on the high bar	N = 4 (2 elites, 2 near elite athletes), explorative lab study, between + within-subject design	Elite athletes only showed less variance in the mechanically important aspects of the performed technique compared to near-elite athletes.
	66	Horan et al. (2011)	Golf	Conducting strokes at a target	N = 38 experts, explorative lab study, within-subject design	The variance of the club head and hand trajectory decreased from the top of the backswing to the ball contact.
	67	Iino et al. (2017)	Table tennis	Conducting strokes at a target as fast and accurately as possible	N = 17 (9 experts, 8 near experts), explorative lab study, between + within-subject design	The vertical racket face angle variance tended to decrease towards ball impact and increased immediately afterwards.
	68	Morrison et al. (2014)	Golf	Conducting strokes at a target	N = 4 experts, explorative lab study, within-subject design	The variance of the club head position trajectory increased from take-off to the top of the backswing and then decreased again until impact.
	69	Morrison et al. (2016)	Golf	Conducting strokes at a target	N = 22 (11 experts, 11 advanced players), explorative field study, between + within-subject design	The variance of the club head position decreased at impact, while the variance of its orientation was lower over the early downswing. The higher-skilled players showed less variance in the club head location than the advanced players.

(*Continued*)

Table 1. Continued.

Mechanism	#	Author(s)	Sport	Task	Type	Main Findings
	70	Nakano et al. (2020)	Basketball	Conducting free throws	N = 8 experts, explorative lab study, within-subject design	The players minimised the speed release to minimise the effect of release parameter errors rather than optimally handling parameter errors. This implies that they pursued a robust strategy according to release errors.
	71	Scholz et al. (2000)	Shooting	Shooting at a target after turns as fast and accurately as possible	N = 9 novices, experimental lab study, within-subject design	The arm configuration variables that do not change the orientation of the gun vector relative to the target did not affect performance and were less controlled than the arm configuration variables with an impact on the orientation of the gun.
	72	Scott et al. (1997)	Athletics	Conducting long jumps	N = 101 (71 elite athletes, 9 advanced athletes, 11 novices), explorative field study and reanalysis of data	Regardless of expertise level, long jumpers generally showed a high variance in the footsteps over the beginning and a low variance over the end of the run-up. The novices showed far more variance over the beginning but almost equal variance over the end.
	73	Sheppard and Li (2007)	Table tennis	Returning services as fast and accurately as possible	N = 24 (12 advanced players, 12 novices), explorative field study, between +within-subject design	In the approach to contact, batters reduced the variability of bat direction and orientation. However, this was not observed for the bat's position, speed and acceleration. Advanced players tended to reduce the variability of the crucial variables when batting at higher speeds.
	74	Tucker et al. (2013)	Golf	Conducting strokes at a target	N = 16 experts, explorative lab study, within-subject design	The variance of the hand trajectory decreased from the top of the backswing to the ball contact. Movement variance was not related to ball speed variance.
	75	van Soest et al. (2010)	Table tennis	Smashing at a target with occluded vision	N = 7 experts, quasi-experimental field study, within-subject design	The variance of the timing and direction of the initial movement of the bat was higher than for the moment of ball-bat contact, both under normal and occluded vision, as well as in an additionally conducted simulation.
Impedance control	76	Blenkinsop et al. (2016)	Gymnastics	Performing handstands under different perturbation levels	N = 12 experts, experimental lab study, within-subject design	Performance under perturbation led to increased muscle stiffness and, ultimately, greater wrist joint torque.
	77	Reeves et al. (2013)	Stick balancing	Balancing a stick with an additional mass at its end	N = 9 novices, experimental lab study, within-subject design	When the task became more difficult (the mass was lower down) and the angular velocity of the stick increased, agonist and antagonist muscle activation increased, meaning that the increased joint stiffness allowed for control of the stick at a higher frequency.

(*Continued*)

Table 1. Continued.

Mechanism	#	Author(s)	Sport	Task	Type	Main Findings
	78	Reeves et al. (2016)	Stick balancing	Balancing a stick with an additional mass at its end	N = 9 novices, experimental lab study, within-subject design	Participants' agonist and antagonist muscle activation increased when tasked to balance a stick with limited visual focus on the lower end of the stick. The increased joint stiffness resulted in better stick control at higher oscillation frequencies.
others	79	Bar-Eli et al. (2007)	Soccer	Saving penalties	N = 286 penalties from top leagues, explorative field study	Whilst the norm is to jump right or left, goalkeepers had the highest chance to save the penalty if they stayed in the goal's centre.
	80	Goodman et al. (2009)	Rifle shooting	Shooting at a target	N = 28 (14 experts, 14 novices), explorative field study, between + within-subject design	In the final phase of shooting, the fluctuations in aiming remained at a constant level. Participants waited until the target was as close as possible to pull the trigger. This effect was found for experts as well as for novices.
	81	Mather (2008)	Tennis	Deciding 'in' or 'out' on tennis strokes under real game conditions	N = 1473 challenges by N = 246 professional athletes, explorative field study	94% of the challenges were within a zone of 100 mm next to the line, and line judges were slightly more accurate than players. A simple perceptual model with intrinsic positional uncertainty could well explain challenges.
	82	Mazyn et al. (2007)	Ball catching	Catching balls under visually occluded conditions	N = 20 novices, experimental lab study, within-subject design	Under occlusion conditions, movements were initiated later, and movement times were shorter than without occlusion. This effect increased after training.

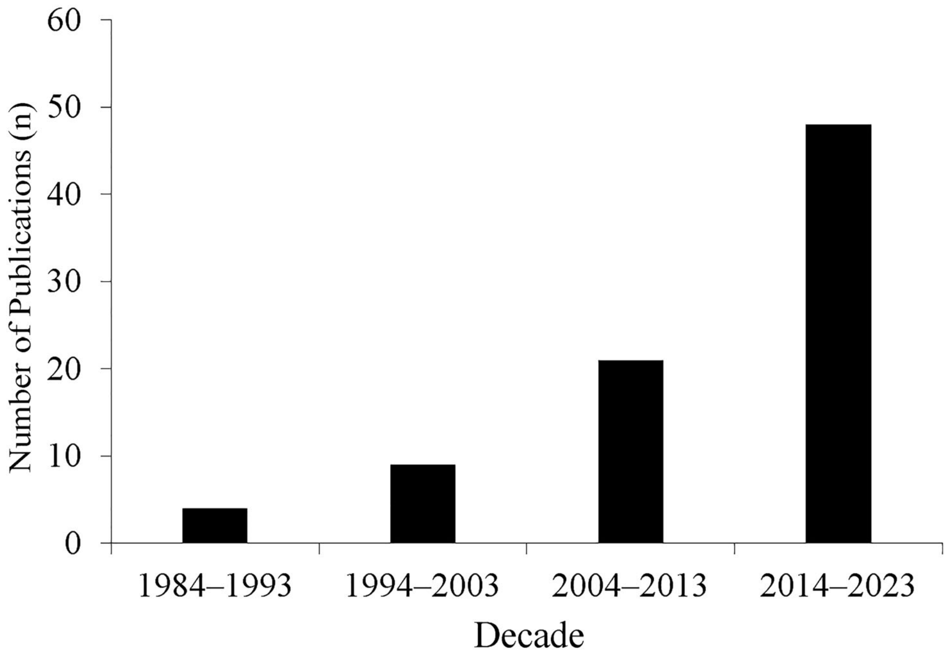

Figure 2. Number of publications on mechanisms for handling uncertainty in sensorimotor control in sports as a function of year of publication.

and characterized by the researched sport, the deployed task, the study type, and the main findings.

Overall, when considering the year of publication, it is clear that the popularity of the topic of uncertainty in sensorimotor control in sports has been growing. As illustrated in Figure 2, the number of publications has rapidly increased over the last ten years.

However, there are extensive differences in research interest when it comes to the five mechanisms (1)–(5) specified in the present paper. While a number of studies focus on the question of how multiple sensory inputs are integrated (16 studies), the largest portion of studies examine integrating prior knowledge (40 studies), either to reduce uncertainty in perception, action or to enhance performance. Aspects of risk optimisation have not been addressed to a notable degree thus far (1 study). Alternately, more attention has been attracted to redundancy exploitation (18 studies), relating to the question of which variables have to be controlled for superior performance and which variables are either not task-relevant or can be compensated. To date, the mechanism of impedance control appears to be under researched in sports science (3 studies). Finally, four studies remained with a focus on handling uncertainty in sensorimotor control in sports that cannot be related to the five mechanisms outlined above.

In regard to the type of the study, considerably more laboratory studies (54 studies) were included in the review than field studies (28 studies). However, the ratio of laboratory to field studies seems to depend on the investigated mechanism. While multisensory integration is rather equally studied in both laboratory (8 studies) and field (8 studies), more laboratory (33 studies) than field (7 studies) studies have been conducted on prior-knowledge integration, whereas there are even slightly more field studies (10 studies) investigating the redundancy exploitation than laboratory studies (8 studies). In general, the findings obtained in laboratory and field studies are in line with each other, so this distinction will not be considered further.

The researched sport, deployed tasks and main findings of the included studies are reported in more detail in the following paragraphs, subdivided by the mechanism assumed to be responsible for handling uncertainty in sensorimotor control in sport.

3.1. Studies on multisensory integration

Of the 16 studies focusing on multisensory integration (see Table 1), almost the entirety reaches the conclusion that multiple sources of sensory information are taken into account in order to control complex sports behaviour. As a rare exception, distorted auditory information was found to have no effect on the performance of a table-tennis counter-hit (Petri et al., 2020). In the other two exceptions, the addition of visual information alongside auditory information did not improve the accuracy of ball-velocity estimations in soccer penalty shots and volleyball smashes (Sors et al., 2017; Sors et al., 2018). In contrast, there is considerable evidence that performance decreases when sensory information that is normally available is disturbed (Heinen et al., 2014; Kennel et al., 2015; Krabben et al., 2018; Santello et al., 2001; Schaffert et al., 2020; Sinnett & Kingstone, 2010; Sors et al., 2017; Takeuchi, 1993) and that performance can be improved by the provision of additional sensory information (Ankarali et al., 2014; Gray, 2009; O'Brien et al., 2020; O'Brien et al., 2021; Zelic et al., 2012). In line with these findings, it had been shown that providing misleading additional sensory information in a hurdling task (Kennel et al., 2015) or experimentally manipulating sound intensity when estimating stroke distances (Cañal-Bruland et al., 2018) decreases performance. However, athletes seem to be capable of compensating for misleading auditory signals over time (Kennel et al., 2015).

Five of the studies on multisensory integration explicitly reference Bayesian inference. However, apart from the fact that any evidence in favour of the integration of different input sources can be counted as generally fitting the Bayesian framework, according to Bayesian inference, multisensory integration should be based on a weighting procedure according to the inputs' estimated reliabilities. In this more specific regard, different levels of reliability are considered in three studies. Petri et al. (2020) reported no effects of auditory information in a table-tennis counter-hit regardless of information's reliability. Kennel et al. (2015) found that delayed – and thus misleading – additional auditory information initially impairs performance in a hurdling task, though this source is increasingly ignored with adaptation over time. In terms of weighting sensory inputs, the most compelling study was conducted by Gray (2009). When only one source of information is available in a baseball-batting simulation, Gray (2009) found that accuracy is best enhanced by visual information. Therefore, this input should be expected to deliver the most reliable information. As consequently predicted, visual information was found to be weighted most heavily when different sources of information are combined in a contradictory manner.

3.2. Studies on prior-knowledge integration

From the total of 82 studies, almost half of the studies (40) are conducted with an either explicit or at least implicit focus on the effects of prior knowledge on perception, action, or performance. There is considerable evidence that prior knowledge influences perception (Arthur & Harris, 2021; Gredin et al., 2018; Harris, Arthur, Vine, et al., 2022b; Nakamoto et al., 2022; Yamamoto et al., 2019) as well as action (Berg & Hughes, 2017, 2020; Eckerle et al., 2012; Gray, 2002; Gredin et al., 2018; Güldenpenning et al., 2023; Güldenpenning et al., 2018; Helm et al., 2020; Leukel et al., 2012; Loffing et al., 2015; Loffing et al., 2016; Magnaguagno et al., 2022; Magnaguagno & Hossner, 2020; McIntyre et al., 2001; Milazzo et al., 2016; Misirlisoy & Haggard, 2014; Sinn et al., 2023; Stevenson et al., 2009; Triolet et al., 2013; Whittier et al., 2022; Zago et al., 2004), and generally improves performance (Abernethy et al., 2001; Crognier & Féry, 2005; Farrow & Reid, 2012; Gray & Cañal-Bruland, 2018; Gredin et al., 2018; Gredin et al., 2019; Gredin et al., 2020c; Gredin et al., 2020a; Helm et al., 2020; Loffing et al., 2015; Loffing & Hagemann, 2014; Magnaguagno et al., 2022; Magnaguagno & Hossner, 2020; Mann et al., 2014; Milazzo et al., 2016; Murphy et al., 2016; Murphy et al., 2018; Navia et al., 2013; Runswick et al., 2018; Wang et al., 2019). Only a few incongruences can be reported; namely, considering the role of participants' expertise levels and the either explicit or implicit provision of contextual information. While Gredin et al. (2018) reported that experts only benefited from explicit (but not from implicit) prior knowledge other studies have shown that experts (but not novices) were able to use implicit prior knowledge (Abernethy et al., 2001; Loffing et al., 2016). Further specifying the findings that prior knowledge generally improves performance, it has been reported that the explicit provision of uncertain prior knowledge can also have an overall negative effect on performance, especially for expert athletes (Jackson et al., 2020; Magnaguagno et al., 2022), a finding that we will discuss in more depth below.

Half of the studies on prior-knowledge integration (20/40 studies) refer to principles of Bayesian inference, which provides a tool for identifying statistically optimal solutions and deriving predictions of human behaviour that can be put to empirical test (Griffiths et al., 2012). However, most of the studies included in the present review just refer to Bayesian inference as a theoretical framework; meaning that the examined behaviours are not compared to statistically optimal solutions and that the reported results are limited to the general conclusion that prior knowledge influences perception, action, or performance per se. Nevertheless, there is clear evidence of a simplified Bayesian model of reliability-weighted integration of prior knowledge and sensory information into perception, supported by 12 studies. However, only sparse evidence (4 studies) favours quantitative optimality derived from the Bayesian framework; particularly demonstrated by Arthur and Harris (2021) and Harris, Arthur, Vine, et al. (2022b) examining gaze strategies in returning bouncing balls. Notably, when it comes to the interactions of prior-knowledge integration with both the level of expertise and the distinction of explicitly instructed vs. implicitly self-generated knowledge as reported above, such calculations on information-gain estimates can also be found in the handball studies published by Magnaguagno et al. (2022). In these studies, the gain estimates were calculated as a function of certainty of explicitly provided contextual knowledge. These calculations are based on the consideration that if explicit prior knowledge is weighted too heavily, the negative consequences in incongruent trials will outweigh the positive effect in congruent trials. Therefore, the congruence between prior knowledge and actual situational probabilities should also be considered as a crucial factor. Regarding the factor of expertise, it seems plausible that experts are better at estimating the reliability of implicit prior knowledge since they know from experience which information is important and trustworthy – as argued by Williams et al. (2011). Taken together, the summarized findings support the call of Gredin et al. (2020b) for a 'Bayesian integration framework' examining the combination of contextual priors and kinematic information in anticipation in sport. However, Bayesian predictions should not only be tested in a more quantitative manner but also be extended from the context of anticipation to the issue of handling noise and uncertainty in complex, naturalistic sensorimotor behaviour in general.

3.3. Studies on risk optimisation

The only included study that focused on risk optimisation was the one published by Bertucco et al. (2020), which showed that inherent noise is taken into account in motor planning in order to optimize potential costs and rewards of the movement outcome. In this study, participants steered a virtual snowboard in a computer game by balancing on a rocker board. As participants passed through different acceleration zones on the slope, they received more financial rewards for reaching faster speeds. When the sensitivity of the rocker board was increased to induce higher inherent noise, the participants chose a larger safety distance to the off-piste penalty zone with the consequence of less acceleration in the middle of the slope. This implies that participants weighed the risk of a penalty with the amount of acceleration – according to different levels of noise – to maximize the financial outcome.

Bertucco et al. (2020) discuss their findings with respect to the theoretical framework of risk optimisation as introduced by Trommershäuser et al. (2008), but also in regards to optimal-control theory (Körding & Wolpert, 2006; Todorov, 2004), which posits that, motor control ultimately comes down to decision making with a focus on maximizing the utility of the movement outcome in the face of sensory, motor and task uncertainty (Wolpert & Landy, 2012).

3.4. Studies on redundancy exploitation

The redundancy exploitation has been introduced above as an alternative – or perhaps supplementary – strategy of weighting available information. Particularly, it provides an alternate approach to handling uncertainty such that sensorimotor noise is only minimized when the noise significantly concerns goal-relevant variables. All 18 studies within this category (Table 1) confirmed that athletes do not try to reduce movement variance in its entirety, but only in certain task dimensions. This is observed in experts behaviour (Bardy & Laurent, 1998; Betzler et al., 2014; Bootsma & van Wieringen, 1990; Burgess-Limerick et al., 1991; Davids et al., 1999; Franks et al., 1985; Hiley et al., 2013; Horan et al., 2011; Iino et al., 2017; Morrison et al., 2014; Morrison et al., 2016; Nakano et al., 2020; Scott et al., 1997; Sheppard & Li, 2007; Tucker et al., 2013; van Soest et al., 2010) as well as in novices behaviour (Burgess-Limerick et al., 1991; Dupuy et al., 2000; Scholz et al., 2000; Scott et al., 1997; Sheppard & Li, 2007). This prioritisation particularly pertains to task-relevant variables in which superior athletes exhibit less movement variance (Bardy & Laurent, 1998; Betzler et al., 2014; Hiley et al., 2013).

In the more recent articles (Iino et al., 2017; Morrison et al., 2016; Nakano et al., 2020), the distinction between goal-relevant and goal-irrelevant variables is theoretically anchored in the uncontrolled-manifold hypothesis (Scholz et al., 2000; Scholz & Schöner, 1999). Accordingly, the variance in the control variables is split into a part that affects the task variables and a part that does not. The ratio of these variances then serves as a measure for the degree of redundancy exploitation, and thus also as a measurement of expertise (Iino et al., 2017; Morrison et al., 2016). To make the distinction between relevant and irrelevant variables for goal achievement, the majority of the reviewed studies draw from the behaviour of experts. In contrast to this purely empirically driven approach, five studies distinguish relevant from irrelevant variables based on functional arguments and compare optimal with actual human behaviour (Betzler et al., 2014; Dupuy et al., 2000; Hiley et al., 2013; Nakano et al., 2020; Scholz et al., 2000). In this regard, the study on underarm precision throwing by Dupuy et al. (2000) demonstrated that people exploit the laws of physics and minimize the variability of the throwing distance adapting both the release angle and speed close to the predicted mechanical optimum.

3.5. Studies on impedance control

Three studies included in the present review focused on handling uncertainty and noise by adapting one's impedance with optimal muscular co-contractions. Empirical findings supporting this strategy include performing a handstand with vs. without vibrations of the floor, where vibrations lead to higher muscle co-contractions and wrist torque stiffness (Blenkinsop et al., 2016). Furthermore, when the task of balancing a more or less inert stick on the hand became more difficult due to visual-focus instructions or mass distribution and the angular velocity of the stick increased, agonist and antagonist muscle activation increased. The increased joint stiffness due to increased activation of agonist and antagonist allowed the stick to be controlled at a higher frequency (Reeves et al., 2013; Reeves et al., 2016).

Although not precisely termed as such, motor control in these studies is interpreted as the optimisation of muscular activities as well as joint stiffness through co-activation (Blenkinsop et al., 2016; Reeves et al., 2013; Reeves et al., 2016). These studies can thus be taken as general empirical support for the notion of impedance control as a means for handling noise-related uncertainty by adapting one's resistance against expected uncertainty. However, more specific predictions regarding the degree to which impedance should be exploited to optimize performance have not been tested so far; though would be a highly desirable exploration for the future.

3.6. Further studies

Due to distinctly different foci, the three remaining studies cannot be assigned to the defined categories. Bar-Eli et al. (2007) show that in penalty situations, soccer goalkeepers tend to jump more often than optimal to the side rather than staying in the middle of the goal. This implies cost functions of the highest relevance are not so obvious, since in the present example, the spectator-related social costs of not acting at all may play a co-decisive role. Goodman et al. (2009) found that rifle shooters wait in a certain range of random movement until the aiming sight happens to point perfectly at the target. The authors explain this strategy by the higher accuracy of the visual than the motor system as a potential further strategy to deal with uncertainty in complex sensorimotor tasks. On the basis of a simple perceptual model with intrinsic positional uncertainty in order to explain challenges in tennis, Mather (2008) recommends, due to perceptual uncertainties, that tennis players should generally take advantage of all the challenges available to them. Finally, Mazyn et al. (2007) tested participants in a trade-off situation where they had to catch a ball and the light was switched of immediately after movement initiation. In this situation participants accepted increased signal-dependent noise of a faster catching movement to gather more ball-flight information.

Although not explicitly relating to one of the mechanisms (1)–(5) identified, these studies should be considered as valuable additions to further our understanding of how humans handle uncertainty in complex motor behaviour.

4. Discussion

This scoping review aimed to examine how humans handle uncertainty in sensorimotor control in naturalistic tasks such as sports and to determine to what extent the well-investigated underlying mechanisms (1)–(5) can be transferred from more fundamental to more complex tasks. The importance of testing the external validity of these mechanisms from fundamental research can be seen in the rapidly growing research interest in uncertainty in sensorimotor control in sports over the last ten years (illustrated in Figure 2). However, there are pronounced differences in research interest when it comes to the five mechanisms (1)–(5).

(1) *Multisensory integration*

Regarding multisensory integration (Ernst & Banks, 2002), the reported empirical findings are generally in line with a Bayesian framework. There is some evidence (Gray, 2009; Kennel et al., 2015) that the weighting of sensory information sources is based on reliability in complex sensorimotor tasks. However, so far, there is no study that compares the empirically observed with the optimal weighting.

(2) *Prior-knowledge integration*

When it comes to prior-knowledge integration (Körding & Wolpert, 2004) based on Bayesian principles, there is clear evidence (12 studies) that the reliability-weighted integration of prior knowledge both improves performance and reduces noise and ambiguity in perception and action in complex sensorimotor tasks. This conclusion perfectly aligns with the review by Gredin et al. (2020b). Moreover, some evidence has been provided that this integration process is close to optimal (Arthur & Harris, 2021; Harris, Arthur, Vine, et al., 2022b; Helm et al., 2020; Whittier et al., 2022).

(3) *Risk optimisation*

Regarding risk optimisation (Trommershäuser et al., 2003), the only study on this mechanism in a complex sensorimotor setting (Bertucco et al., 2020) provides evidence that the utility of movement outcome is maximized in the face of motor noise.

(4) *Redundancy exploitation*

Concerning the redundancy exploitation, theoretically substantiated by the uncontrolled-manifold hypothesis (Scholz & Schöner, 1999) or the principle of minimal intervention (Todorov & Jordan, 2002), 13 studies showed that experts as well as novices distinguish between task-relevant and task-irrelevant variables. Five further studies demonstrated that variability is only reduced in functional goal-relevant variables to an optimal degree (Dupuy et al., 2000).

(5) *Impedance control*

Three studies that considered impedance control (Burdet et al., 2001; Hogan, 1984) in complex sensorimotor tasks provide evidence that perturbations can be absorbed using higher muscle stiffness resulting from muscular co-contraction.

Taken together, these findings – from a broad range of study types and investigated tasks – show that the mechanisms (1), (2), and (4) have been convincingly empirically proven in naturalistic complex sensorimotor tasks. The mechanisms (3) and (5) remain under-researched with some empirical evidence for their external validity in a naturalistic environment. Moreover, regarding the (frequently) self-imposed theoretical framework, the empirical tests of the mechanisms did not always match to a satisfactory extent. Future research should thus more specifically focus on how these mechanisms are utilized by testing clear predictions derived from theoretical models rather than just scratching the surface to show that, for instance, prior knowledge is considered per se. In this respect, the study of Arthur and Harris (2021) could be regarded as a landmark for future research. In this study, not only empirically quantitative predictions of an optimal Bayesian observer were made and compared with actual behaviour, but also eye movements as the first movements in anticipatory behaviour were investigated. Examining eye movements may, therefore, provide conclusive insights into the process of prior-knowledge integration. Further, Magnaguagno et al. (2022) presented quantitative predictions about expected anticipatory behaviour, broadening the empirical focus by considering the effects of further variables, such as the level of expertise or implicit prior-knowledge accumulation versus explicit prior-knowledge provision can be expected to provide additional depth to understand the mechanisms in even more detail. Finally, while considerable evidence for mechanisms (1), (2), and (4) has been provided, the mechanisms of (3) risk optimisation and (5) impedance control are still poorly researched in sports science so far. Therefore, further research is urgently required to determine these mechanisms' additional or interacting contributions to handling uncertainty in sensorimotor control in naturalistic complex, in particular sports-related tasks. Furthermore, it becomes clear that for future research, different emphases should be set for each mechanism.

Having discussed five explanatory mechanisms largely in isolation, the question arises as to whether and, if so, how these mechanisms might be placed in a single theoretical framework. In seeking such a framework, it should first be noted that not all of the studies included in this scoping review are based on a cognitive approach. In contrast to the Bayesian idea of an accentuated cognitive weighting of probabilities, Gray (2002) applies an alternative model with high predictive power; namely a non-Bayesian two-state Markov model with a fairly simple win-stay, loose-switch heuristic. Moreover, dynamical-systems theory and the ecological approach to movement coordination can undoubtedly contribute to the examination of handling uncertainty. As illustrated in this review by juxtaposing the cognitive principle of minimal intervention (Todorov & Jordan, 2002) and the uncontrolled-manifold hypothesis (Scholz & Schöner, 1999) rooted in dynamical-systems theory – cognitive and ecological explanations of handling uncertainty in human behaviour may arrive at similar conclusions (e.g. in comparison, Davids et al., 1999, p. 439; Franklin & Wolpert, 2011, p. 429). On this basis, a unifying framework considering the empirical evidence from fundamental research (for reviews, e.g. Franklin & Wolpert, 2011; Gallivan et al., 2018; Körding & Wolpert, 2006; Todorov, 2004) as well as the empirical evidence in more complex, in particular sports-related tasks seems even more highly desirable. To this end, the assumption that coordinated behaviour requires sufficiently reliable online predictions of changes in the world might provide a guiding direction. This idea is presented in more detail in Figure 3, where the framework of optimal feedback control (according to Körding & Wolpert, 2006; and Todorov, 2004) is used to integrate the highlighted mechanisms (1)–(5).

This proposed model is based on the assumption of a close interaction between an internal and an external control loop. The motor controller generates efferent signals dependent on both the estimation of the current state and the specifics of the motor goal according to the utility function. In the internal loop, a forward model predicts how the current state would change based on an internal copy of emitted efferences. In the external loop, the actual changes produced by the biomechanical plant under altering conditions in the external world are observed by the sensory systems. This observation is carried out with a considerable time delay and is corrupted by noise and ambiguities. To reduce uncertainty about the current state, the mechanisms of (1) multisensory integration and (2) prior-knowledge integration come into play. These mechanisms form a continuous integration of all available information sources – perhaps either by Bayesian or alternative procedures – including internal state predictions derived from the forward model. Risk optimisation as mechanism (3) becomes relevant when, on the basis of the estimated state, details of the current motor goal are specified. This regards the intended effect as well as a utility function, where the costs of all possible movement outcomes are considered – especially due to noise and delays in movement execution. Based on internal predictions of the resulting effects, the motor controller determines which manipulations of control variables are required to achieve the desired effect whilst preferably staying within or entering the subspace of optimal task-solutions – thereby instantiating mechanism (4) on redundancy exploitation. Finally, as an alternative to actively handling noise and delays, the motor controller may also adapt the impedance of parts of the biomechanical plant as an optimal solution to the given motor task in terms of mechanism (5) of impedance control such that external perturbations are immediately dampened.

In Figure 3, we chose optimal feedback control as our theoretical framework because it has become a highly influential theory within the engineering approach to understanding sensorimotor behaviour over the past few decades and, moreover, has been widely confirmed empirically (for reviews, e.g. Franklin & Wolpert, 2011; Gallivan et al., 2018; Körding & Wolpert, 2006; Todorov, 2004). In the present context, however, the model serves only as a framework to systematically place and illustrate basic mechanisms for

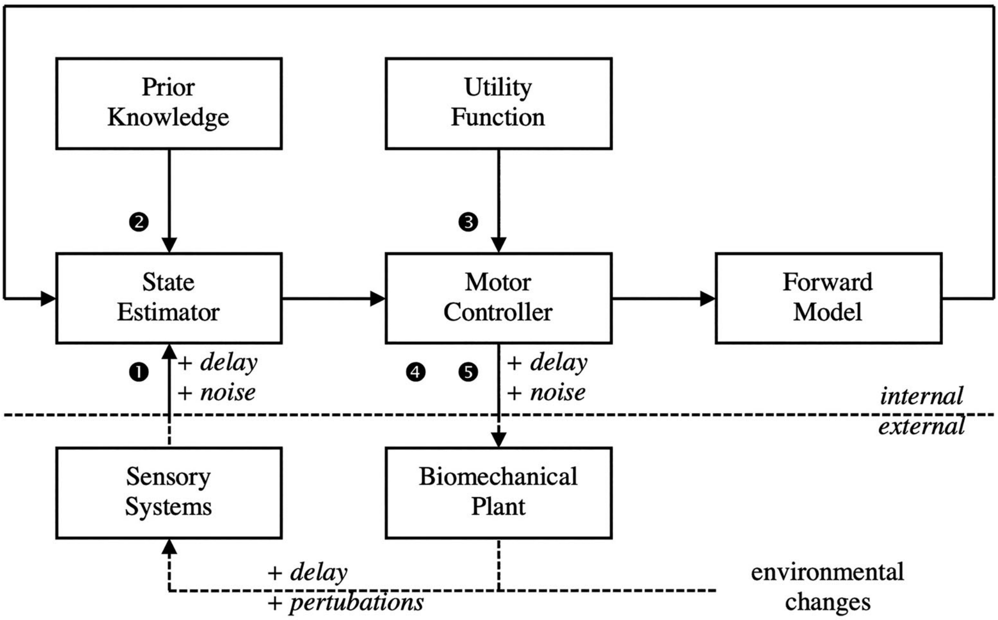

Figure 3. Optimal feedback-control loops (Körding & Wolpert, 2006, p. 323; Todorov, 2004, p. 910; combined and modified by the authors) with indication of mechanisms (1)–(5) for handling uncertainty in sensorimotor control: (1) multisensory integration, (2) prior-knowledge integration,(3) risk optimisation, (4) redundancy exploitation, and (5) impedance control.

dealing with uncertainty in complex sensorimotor behaviour. This being said it is obvious that alternative models could have been chosen as a framework as well. In our view, this is particularly true for the idea of active inference (Friston, 2010; in regards to prior-knowledge integration, see Harris, Arthur, Broadbent, et al., 2022a), which operates more at a neuro-implementational rather than an engineering level of explanation. While certain differences in specific theory elements are discussed in the scientific community (for details, see Friston, 2011), the two approaches share the theoretical core of viewing perception and action as fundamentally probabilistic based on online predictions and the integration of information according to Bayesian principles. More specifically, and referring to Figure 3, the approaches share key theoretical concepts by asserting the need for an internal forward/generative model, Bayesian integration of sensory information and prior knowledge/beliefs, and behavioural control optimisation according to costs/surprise. This convergence at the level of key concepts is, in our view, good news for joint and coherent progress in this area.

In precisely this sense, the present review and proposed integrative framework should primarily be understood as a heuristic for stimulating future research on handling uncertainty in complex sensorimotor behaviour, including interactions between multiple mechanisms; for example, how prior knowledge affects impedance control. It is expected that such empirical work will advance our understanding at a theoretical level, hopefully moving us from a general framework to a concise theory enabling the derivation of novel and testable predictions. We would be grateful if readers felt invited to participate in this scientific endeavour.

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Data availability statement

Data available within the article or its supplementary materials.

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Appendices

Appendix A. PRISMA-ScR checklist

Table A1. Preferred reporting items for systematic reviews and meta-analyses extension for scoping reviews (PRISMA-ScR) checklist.

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	0
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	1
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	2–4
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g. population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	2–4
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g. a Web address); and if available,	*

(*Continued*)

Table A1. Continued.

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
		provide registration information, including the registration number.	
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g. years considered, language, and publication status), and provide a rationale.	4–6
Information sources*	7	Describe all information sources in the search (e.g. databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	5
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	Appendix B
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e. screening and eligibility) included in the scoping review.	4–6**
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g. calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	4–6
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	4–5
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	***
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	****
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	5–6
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	Table 1
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	***
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	Table 1
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	6–12
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	12–16
Limitations	20	Discuss the limitations of the scoping review process.	12–16
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	12–16
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.-	

Comments
***Item 5, protocol and registration**: No protocol was preregistered. However, specific objectives of the review and methods were defined a priori:

(1) Objectives: To provide a complete overview of peer-reviewed research on the topic of handling uncertainty in sensorimotor control in sports, focusing on collating all empirical evidence and contrasting different theoretical approaches.
(2) Methods: Based on the review's objective, (a) eligibility criteria (pp. 4–6), (b) information sources (pp. 5–6), and (c) search strategy (pp. 5–6) were specified before conducting the review.

****Item 9, study selection:** Two raters independently screened all titles and abstracts. The abstracts were then merged, meaning that the record remained in the pool for full-text screening if at least one of the two raters judged the abstract as fulfilling the inclusion criteria. Furthermore, in an iterative process, the reference lists of all included studies were systematically screened, and in appendix C is documented which article is referred to by the other articles. The full-text screening was conducted by the first author. Potentially ambiguous cases were discussed with the other authors and resolved by consensus after referring to the inclusion and exclusion criteria.

*****Item 12 / 16, critical appraisal**: Only studies published in peer-reviewed journals were considered. Based on the current review's objective, no quality assessment of individual studies was sought. However, regarding a critical appraisal, theoretical assumptions and their empirical foundation were critically discussed.

******Item 13 synthesis of results**: Based on the current review's objective and the inherent diversity in methodologies and different mechanisms to handle uncertainty, the synthesis of the evidence was made by comparing the number of studies supporting a mechanism and how powerful the theoretical prediction was made (e.g. normative models).

Appendix B. Electronic search strategy

Last search:
15 July, 2023, via Campus Network …

PsycINFO (via OvidSP)
((uncertainty or noise) and (sensor* or motor) and control and movement and sport).af.
limit 1 to (peer reviewed journal and english language and '0110 peer-reviewed journal' and english)

PubMed pubmed.gov
((((uncertainty OR noise)) AND (sensor* OR motor)) AND control) AND sport) AND movement

ScienceDirect
(uncertainty OR noise) and (sensory OR motor) and control and sport and movement

Scopus
(uncertainty OR noise) AND (sensory OR motor) AND control AND sport AND movement AND (LIMIT-TO (PUBSTAGE, 'final')) AND (LIMIT-TO (DOCTYPE, 'ar')) AND (LIMIT-TO (LANGUAGE, 'English')) AND (LIMIT-TO (SUBJAREA, 'PSYC') OR LIMIT-TO (SUBJAREA, 'SOCI'))

SportDiscus (via EBSCOhost)
(uncertainty OR noise) AND (sensor* OR motor) AND control AND sport AND movement

Web of Science
uncertainty OR noise (All Fields) and sensor* OR motor* (All Fields) and control (All Fields) and sport (All Fields) and movement (All Fields) and Articles (Document Types) and English (Languages)

Appendix C

Table C1. Identification of the studies.

	Author(s)	cited in	found by
1	(Abernethy et al., 2001)	3,14,18,28,32,36,40,42,41,43,45,53,54,57,75,78,71,72	initial search
2	(Ankarali et al., 2014)		initial search
3	(Arthur & Harris, 2021)	30	initial search
4	(Bar-Eli et al., 2007)	71	reference list
5	(Bardy & Laurent, 1998)	16,35,64	initial search
6	(Berg & Hughes, 2017)	7	initial search
7	(Berg & Hughes, 2020)		initial search
8	(Bertucco et al., 2020)		additional
9	(Betzler et al., 2014)	52	reference list
10	(Blenkinsop et al., 2016)		initial search
11	(Bootsma & van Wieringen, 1990)	5,12,15,35,51,52,53,63,68,77	initial search
12	(Burgess-Limerick et al., 1991)		initial search
13	(Cañal-Bruland et al., 2018)	25,65,72	reference list
14	(Crognier & Féry, 2005)	40,41,43,49,53,54,57,75	reference list
15	(Davids et al., 1999)		initial search
16	(Dupuy et al., 2000)	56	reference list
17	(Eckerle et al., 2012)	7,69	initial search
18	(Farrow & Reid, 2012)	21,24,28,29,32,36,40,41,43,44,45,49,53,54,61,63,78,	initial search
19	(Franks et al., 1985)	5,11,12,15	initial search
20	(Goodman et al., 2009)		initial search
21	(Gray & Cañal-Bruland, 2018)	3,25,26,27,29,30,32,36,53,78	initial search
22	(Gray, 2002)	23,36,41,44,45,53,54,75	reference list
23	(Gray, 2009)	21,25,26,27,38	reference list
24	(Gredin et al., 2018)	2,11,12,13,16,21,22,29,34	initial search
25	(Gredin et al., 2019)	26,27,44	reference list
26	(Gredin, Bishop, et al., 2020a)		additional
27	(Gredin, Broadbent, et al., 2020c)	26	initial search
28	(Güldenpenning et al., 2018)	29,36	reference list
29	(Güldenpenning et al., 2023)		reference list
30	(Harris, Arthur, Vine, et al., 2022b)		reference list
31	(Heinen et al., 2014)	38	reference list
32	(Helm et al., 2020)	26,29,36,43,44,53	initial search
33	(Hiley et al., 2013)		initial search
34	(Horan et al., 2011)	51,52,76	initial search
35	(Iino et al., 2017)		initial search
36	(Jackson et al., 2020)	29,44	reference list
37	(Kennel et al., 2015)		additional
38	(Krabben et al., 2018)		initial search
39	(Leukel et al., 2012)		initial search
40	(Loffing & Hagemann, 2014)	24,28,32,41,42,43,44,45,53,54,63,78	reference list
41	(Loffing et al., 2015)	24,27,28,29,32,36,42,43,44,53,54,63,78,	initial search
42	(Loffing et al., 2016)	32,54,60,78	initial search
43	(Magnaguagno & Hossner, 2020)	44	reference list
44	(Magnaguagno et al., 2022)		initial search
45	(Mann et al., 2014)	21,24,27,28,29,32,36,41,43,44,49,53	initial search
46	(Mather, 2008)		additional
47	(Mazyn et al., 2007)		initial search
48	(McIntyre et al., 2001)	81	reference list
49	(Milazzo et al., 2016)	29,36,54,60	reference list
50	(Misirlisoy & Haggard, 2014)	41	reference list
51	(Morrison et al., 2014)	52	reference list
52	(Morrison et al., 2016)	35	reference list
53	(Murphy et al., 2016)	24,25,36,43,44,54,63,72,78	reference list
54	(Murphy et al., 2018)	43,44,78,60	reference list
53	(Nakamoto et al., 2022)		reference list
56	(Nakano et al., 2020)		initial search
57	(Navia et al., 2013)	24,25,27,29,32,36,41,43,44,45,49,53,54,78	reference list
58	(O'Brien et al., 2020)		initial search

(*Continued*)

Table C1. Continued.

	Author(s)	cited in	found by
59	(O'Brien et al., 2021)		initial search
60	(Petri et al., 2020)		initial search
61	(Reeves et al., 2013)	62	reference list
62	(Reeves et al., 2016)		initial search
63	(Runswick et al., 2018)	25,26,27,29,64,78	reference list
64	(Santello et al., 2001)	6	reference list
65	(Schaffert et al., 2020)		additional
66	(Scholz et al., 2000)	52	reference list
67	(Scott et al., 1997)	35,51,52,68	reference list
68	(Sheppard & Li, 2007)	35	reference list
69	(Sinn et al., 2023)		reference list
70	(Sinnett & Kingstone, 2010)	13,82	reference list
71	(Sors et al., 2017)	13,60,65,72	initial search
72	(Sors et al., 2018)	65	reference list
73	(Stevenson et al., 2009)	3,44	reference list
74	(Takeuchi, 1993)	13,38,65,71,72	reference list
75	(Triolet et al., 2013)	24,26,53,54,63	initial search
76	(Tucker et al., 2013)	51,52	reference list
77	(van Soest et al., 2010)	35	reference list
78	(Wang et al., 2019)	60	reference list
79	(Whittier et al., 2022)		reference list
80	(Yamamoto et al., 2019)		initial search
81	(Zago et al., 2004)	3	reference list
82	(Zelic et al., 2012)		initial search