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When Navigation Becomes Unreliable: Recognition, Verification and Recovery in Cranial, Stereotactic and Spinal Neurosurgery

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Abstract

Image-guided navigation supports operative planning, instrument localisation and trajectory control in cranial, stereotactic and spinal neurosurgery. Its reliability, however, depends on the continued validity of registration, tracking and anatomical correspondence throughout the procedure. Navigation discordance may arise when these relationships change, and the discrepancy may not be immediately apparent from the navigation display alone. This critical narrative review examines the mechanisms of navigation discordance, methods used to verify suspected inaccuracies, and strategies that may support recovery across cranial, stereotactic and spinal procedures. Particular attention is given to the distinction between registration accuracy, final technical accuracy, workflow reliability and clinically meaningful outcomes. The review also considers intraoperative MRI, intraoperative ultrasound, stereotactic verification, spinal navigation, augmented reality and human factors relevant to the recognition of unreliable guidance. Based on a structured synthesis of the literature, we propose a five-stage response framework comprising detection, pausing image-dependent action, independent verification, recovery and documentation. We also propose a minimum reporting dataset for navigation-related interruptions to improve consistency in the description of discordance, corrective actions and their consequences. The proposed framework is conceptual and has not undergone formal expert consensus, prospective usability testing or clinical outcome validation. It is intended to support discussion, local protocol development, reporting and future research rather than serve as a validated clinical algorithm. More consistent reporting of navigation interruptions and recovery processes may improve understanding of how image-guided systems perform under real operative conditions.

Categories: Radiology, Healthcare Technology, Neurosurgery
Keywords: brain shift, image-guided surgery, intraoperative imaging, neuronavigation, neurosurgery, patient safety, registration error, spinal navigation, surgical navigation, surgical workflow

Introduction And Background

Neuronavigation allows preoperative and intraoperative imaging to inform instrument localisation, trajectory planning and surgical decision-making within the operating theatre. Its accuracy depends on several distinct processes, including image acquisition, registration, tracking and maintenance of correspondence between the displayed image and operative anatomy. In rigid point-based registration, fiducial-registration error (FRE) and target-registration error (TRE) are not interchangeable. TRE is influenced by fiducial geometry and localisation uncertainty, and a low FRE does not necessarily imply equivalent accuracy at a remote operative target [1]. An apparently satisfactory registration result should therefore not be assumed to establish uniform accuracy throughout the operative field.

In this review, navigation discordance is used as the overarching term for a clinically relevant disagreement between displayed image-guidance information and independently assessed operative anatomy or instrument position. Terms such as navigation error, mismatch, discrepancy and unreliability are used only when describing a more specific mechanism or observation. Contemporary neuronavigation may use point-based fiducial registration, surface-matching techniques or image-based and automatic registration workflows incorporating intraoperative imaging. Instrument and patient-reference tracking may use optical or electromagnetic technologies. The relationship between FRE and TRE described by Fitzpatrick et al. is most directly established for rigid point-based registration [1]. The broader principle that a favourable global registration metric does not necessarily establish accuracy at every operative target is therefore applied cautiously to other registration approaches rather than assumed to be quantitatively equivalent across systems.

Navigation inaccuracies may arise at several stages of the workflow. Jensen et al. proposed a general framework for stereotactic inaccuracy encompassing imaging, registration, mechanical accuracy, target planning and adjustment, and trajectory planning and adjustment [2]. This distinction is clinically important because a navigation display may remain visually coherent even when one of the assumptions underlying its accuracy is no longer valid. A discrepancy caused by registration error may therefore require a

different response from one caused by mechanical deviation, trajectory-planning error or a change in operative anatomy.

Technological developments have sought both to improve registration accuracy and to compensate for anatomical change during surgery. Özbek et al. evaluated a target-specific registration approach under controlled experimental conditions, illustrating the precision that may be achievable with a dedicated cranial registration system [3]. Their study used a phantom skull and electromagnetic tracking, and the findings should not be assumed to generalise directly to optical tracking systems or to intraoperative conditions after anatomical deformation. Registration accuracy established before operative intervention may become less representative as anatomy changes during the procedure.

Brain deformation is an important example of this problem. Assis et al. reviewed data-driven methods for modelling and correcting intraoperative brain deformation, identifying challenges including heterogeneous datasets, variable validation strategies, uncertainty, generalisability and translation to clinical use [4]. These limitations are particularly relevant during cranial tumour surgery, where cerebrospinal-fluid loss, gravity, retraction, swelling and tissue removal may progressively alter the relationship between preoperative imaging and the operative field.

Related concerns arise in spinal instrumentation and stereotactic procedures, although the underlying mechanisms differ. In spinal navigation, displacement of a reference array or changes in vertebral position may alter the relationship between the navigation dataset and the target level. In stereotactic procedures, inaccuracies may arise from imaging, registration, mechanical guidance, target definition or trajectory planning [2]. Across these settings, the shared clinical problem is not a single universal error mechanism. It is the need to recognise when displayed guidance no longer corresponds sufficiently with the operative target and to determine how confidence can be independently re-established before image-dependent action continues.

This critical narrative review examines selected mechanistic, clinical and human-factors evidence concerning navigation discordance and intraoperative recovery. It is not a systematic review and does not claim exhaustive literature retrieval or pooled effectiveness estimates. Cranial, stereotactic and spinal procedures are considered together because, despite important differences in anatomy, registration technique, tracking technology and procedural risk, each depends on maintaining reliable correspondence between a virtual representation, a tracked instrument or trajectory, and the intended operative target. The mechanisms of failure are not assumed to be equivalent. Instead, these procedures are considered together to examine the shared clinical problem of recognising unreliable guidance, independently verifying suspected discordance, restoring confidence where possible and documenting the recovery process.

Building on the existing descriptions of navigation and stereotactic error, this review proposes a cross-procedure conceptual framework integrating detection, pausing image-dependent action, independent verification, recovery and documentation. The framework is intended to support discussion, local protocol development, standardised reporting and future validation. It is not presented as a clinically validated rescue algorithm.

Review

Methods and source selection

This article was undertaken as a critical narrative review rather than a systematic review. Literature was identified through targeted searches of PubMed/MEDLINE, supplemented by reference-list screening of relevant reviews and primary studies. Searches were updated to November 14, 2026. Search terms were combined according to the topic under consideration and included combinations of 'neuronavigation', 'navigation error', 'registration error', 'target registration error', 'brain shift', 'intraoperative MRI', 'intraoperative ultrasound', 'spinal navigation', 'reference frame', 'robotic spine surgery', 'stereotactic surgery', 'deep brain stimulation', 'stereoelectroencephalography', 'automation bias' and 'augmented reality'.

Peer-reviewed clinical studies, technical studies, systematic reviews and methodological papers were considered when they directly informed one or more of the following: mechanisms of navigation inaccuracy; recognition or verification of suspected navigation discordance; intraoperative imaging or physiological methods that may restore confidence in guidance; human factors affecting reliance on navigation; and reporting of navigation-related interruptions. Priority was given to higher-level clinical evidence where available, particularly randomised trials and systematic reviews, while representative technical and observational studies were retained where they addressed mechanisms or workflows not evaluated in trials.

Source selection was purposive and section-specific. Cranial literature was selected to address registration, brain deformation and updated intraoperative imaging; stereotactic literature to address targeting, verification and electrode-placement accuracy; spinal literature to address reference-dependent navigation and instrumentation; and human-factors literature to address automation bias and interface reliability. Studies without a clear relationship to these questions were not used solely to broaden coverage. No formal risk-of-bias tool or quantitative synthesis was undertaken because the purpose of the review was conceptual

and mechanistic rather than estimation of a pooled treatment effect. This approach introduces a risk of selection bias, and the literature discussed should not be considered exhaustive.

The proposed five-stage response sequence was developed by the authors through structured synthesis of recurring principles identified across these sources. These included recognition of discordance, interruption of image-dependent action, independent verification, restoration or replacement of reliable guidance, and documentation of the event and corrective response. The stages were not derived through formal expert consensus or prospective testing. They are therefore presented as a conceptual framework for evaluation and future validation rather than a clinical algorithm.

What does a navigation error actually measure?

A low FRE does not guarantee a low TRE. Fiducials may cluster near an accessible surface while the operative target lies deeper or outside their spatial distribution. Classical work on rigid point-based registration established that fiducial geometry and localisation uncertainty influence expected accuracy at the target [1]. A global numerical registration score therefore cannot substitute for verification at the relevant operative site.

This principle is most directly applicable to point-based rigid registration. Surface-matching, automatic image-based registration and systems incorporating updated intraoperative imaging use different methods to establish spatial correspondence. The quantitative relationship between FRE and TRE should not be assumed to transfer unchanged between these approaches. The clinically relevant principle is narrower: a favourable system-level registration metric does not by itself prove satisfactory accuracy at every operative target.

Different sources of inaccuracy should also be distinguished. Imaging error may arise from acquisition, distortion or segmentation; registration error concerns correspondence between image and patient; mechanical error concerns the relationship between the planned and delivered trajectory; and subsequent anatomical change can invalidate a transformation that was initially accurate [2]. Reporting a single value as 'navigation accuracy' can therefore obscure the mechanism responsible for a discrepancy. A tracking system may continue to function precisely while the displayed anatomy becomes inaccurate after brain deformation. Conversely, an accurately registered dataset may still be associated with an unsuitable trajectory plan.

Özbek et al. reported a mean measured TRE of 0.22 ± 0.08 mm using their target-specific cranial registration system [3]. This was a phantom skull study using electromagnetic tracking. It demonstrates the precision achievable by that device under controlled experimental conditions, but does not establish equivalent performance with optical systems or during surgery after dural opening, tissue deformation or resection. Technical registration precision, intraoperative anatomical fidelity and clinical outcome are separate endpoints.

Cranial surgery: navigation discordance during intraoperative brain deformation

The brain is not a rigid structure. Cerebrospinal fluid loss, gravity, swelling, retraction and tissue removal can change local anatomy during craniotomy. These changes are spatially non-uniform, and a rigid transformation that remains satisfactory at one landmark may become inaccurate elsewhere. Assis et al. reviewed data-driven approaches to modelling and correcting brain deformation and identified continuing challenges relating to heterogeneous datasets, validation, uncertainty and generalisability [4]. Such methods are relevant to correction of brain shift, but they do not establish which intraoperative response is safest when discordance is first suspected.

Updated imaging provides one means of reassessing anatomy after the preoperative dataset has become less representative. In the randomised trial by Senft et al., complete resection was achieved in 23 of 24 evaluable patients assigned to intraoperative magnetic resonance imaging (iMRI) compared with 17 of 25 controls, corresponding to 96% and 68%, respectively [5]. More recently, Li et al. randomised 321 patients with glioma to high-field iMRI or conventional neuronavigation and reported gross-total resection in 83.85% and 50.00%, respectively [6]. These trials support the ability of updated imaging to alter resection assessment, but neither should be interpreted as direct evidence that a particular response to navigation discordance prevents neurological injury.

The certainty of the wider evidence is important. A Cochrane review concluded that intraoperative imaging may increase the extent of glioma resection but judged much of the evidence available at that time to be of low or very low certainty, particularly for neurological and longer-term outcomes [7]. Subsequent systematic reviews and meta-analyses have continued to report greater rates of gross-total resection with iMRI, while also identifying heterogeneity and more limited evidence for downstream neurological or survival benefit [8,9]. In this context, iMRI is best regarded as a potential tool for renewed anatomical verification in selected operations rather than evidence that navigation recovery itself improves safety.

Intraoperative ultrasound (iUS) offers a more readily repeatable means of obtaining contemporaneous anatomical information where iMRI is unavailable or impractical. Dixon et al. describe its clinical implementation, including the importance of image quality, acoustic artefact and operator experience [10]. The modality can provide an updated view of tissue and the resection cavity, but its interpretation is itself affected by altered tissue appearance, acoustic artefact and the evolving operative cavity. Independent verification therefore does not mean assuming that a second modality is infallible. It requires understanding whether the second source of information is sufficiently independent of the suspected failure mechanism.

Prospective studies illustrate both the potential and the limitations of ultrasound-based correction. Iversen et al. evaluated automatic correction of brain shift in 13 tumour resections and reported an improvement in median landmark alignment from 5.12 mm to 2.72 mm [11]. The system was sufficiently accurate for intraoperative guidance in nine of 13 cases. Importantly, postoperative analysis identified limitations and modifications that would have produced sufficient accuracy in all 13 cases. This distinction is relevant because it shows both the feasibility of correction and the difference between prospective intraoperative performance and retrospective optimisation.

Moiyadi et al. evaluated automated rigid MRI-iUS fusion using 79 datasets from 24 patients [12]. The mean TRE improved from approximately 4.7 mm to 3.5 mm. The improvement was significant before dural opening, after dural opening and after partial resection, but was not significant after completion of resection, when anatomical disruption was greatest. These findings suggest that correction performance may depend on the operative stage and that a technique that performs well earlier in surgery may become less reliable after extensive tissue removal. The study also included commercial relationships relevant to the imaging technologies under evaluation, which should be considered when interpreting technical performance.

West et al. prospectively studied navigated iUS in 40 patients with intracranial tumours, including 18 metastases, and reported 95% concordance between intraoperative ultrasound-based and postoperative MRI-based assessments of extent of resection [13]. Median ultrasound sweep and image-processing times were 5.5 and 29.9 seconds, respectively. These timings describe image acquisition and processing rather than the complete time required for equipment set-up, registration, interpretation and operative decision-making. The study primarily evaluated extent-of-resection assessment and feasibility rather than a defined navigation-rescue protocol, so its findings support rapid repeat imaging but should not be used as a direct estimate of recovery time after navigation failure.

In a randomised study of conventional B-mode ultrasound in glioblastoma surgery, complete resection was recorded in eight of 23 assessed ultrasound patients and two of 24 controls, corresponding to 35% and 8%, respectively [14]. No clear between-group improvement in functional outcome or survival was demonstrated. Taken together, the cranial literature shows that updated imaging can improve anatomical information and, in some settings, extent of resection. It provides considerably less evidence that any specific sequence for recognising and correcting navigation discordance reduces neurological complications. For that reason, iMRI and iUS are considered here as tools that may support verification and recovery, not as validation of the response framework proposed below.

Stereotactic procedures: accuracy, verification and the consequence of small errors

Stereotactic procedures differ from cranial tumour resection because the operative target may be small, deep and not directly visible. Accuracy therefore depends on the complete chain from imaging and registration through target definition, trajectory planning and mechanical delivery [2]. A discrepancy of only a few millimetres may be clinically important when the target is a compact nucleus or when an electrode trajectory passes close to a vessel or other critical structure.

Deep brain stimulation (DBS) provides a useful example of independent verification. Rajabian et al. reported 650 consecutive frame-based DBS procedures using stereotactic intraoperative MRI for guidance and verification [15]. Among 1,201 implanted leads, the final mean targeting error was 0.9 ± 0.3 mm. Thirty-seven leads, representing 3%, underwent immediate intraoperative relocation after imaging showed that the initial position was not anatomically satisfactory. This demonstrates the practical value of verifying the delivered lead position before the opportunity for immediate correction has passed. It does not establish a universal numerical threshold for relocation, since acceptable error depends on the target, trajectory and clinical context.

Stereoelectroencephalography (SEEG) similarly illustrates the importance of considering the targeting method when interpreting an accuracy value. Girgis et al. compared frame-based and frameless SEEG insertion in 23 patients and 81 electrodes [16]. In that series, eight of 45 frameless electrodes missed their intended target and were not clinically useful, compared with none of 36 frame-based electrodes. The study was relatively small and evaluated specific techniques at a single centre, but it demonstrates that registration and delivery method can materially affect the relationship between a planned and achieved stereotactic target.

Verification in functional stereotaxy may also include physiological information. Microelectrode recording and intraoperative stimulation can provide information about whether the trajectory traverses expected physiological structures, although these signals answer a different question from imaging confirmation of the final lead position [17]. Physiological and anatomical verification should therefore be regarded as complementary rather than interchangeable. Depending on the procedure, intraoperative or postoperative CT or MRI may establish electrode location, while neurophysiological findings may help determine whether the intended functional target has been reached.

Direct evidence describing the frequency and management of unexpected navigation failure during DBS, SEEG and other stereotactic procedures remains less developed than literature reporting final targeting accuracy. This is itself an important limitation of the evidence base. A lead that is corrected intraoperatively may ultimately be counted as accurately positioned, while the preceding discrepancy and corrective action are not consistently reported. The same distinction between final technical success and the reliability of the recovery process therefore applies to stereotactic procedures.

Spine surgery: a rigid image and a moving reference

Spinal navigation usually relies on treating the registered anatomy and its reference as a rigid spatial relationship. The reference array, however, is not physically fixed to every vertebra that may subsequently be instrumented. Patient repositioning, traction, deformity correction or movement of the reference relative to the operative target can therefore challenge the validity of a previously satisfactory transformation. This is a mechanistic consequence of reference-dependent rigid navigation rather than an estimate of how frequently clinically important reference displacement occurs.

Local verification is particularly important before a narrow or high-risk osseous corridor is breached. The tolerance for unexplained disagreement is not uniform across the spine. Shree Kumar et al. evaluated 1,152 screws placed with intraoperative image-guided navigation and reported cortical violation in 17 of 241 cervical screws (7.05%), 11 of 300 thoracic screws (3.67%), and 22 of 611 lumbar screws (3.60%) [18]. These unadjusted regional rates do not establish that navigation is intrinsically less accurate in one region after accounting for case mix and anatomy. They do, however, illustrate why an aggregate screw-accuracy percentage may conceal clinically different consequences of spatial error.

New registration strategies attempt to reduce dependence on a static transformation. Liebmann et al. evaluated automatic registration with continuous pose updates in a markerless spine-navigation system using experimental and ex vivo assessments [19]. Such work is relevant to the problem of stale registration, but it does not yet establish routine patient-level clinical performance. Automated updating also introduces other dependencies, including segmentation accuracy, visibility, occlusion and deformity. Removing a conventional reference array therefore changes the failure modes rather than eliminating registration uncertainty.

Givens et al. used a Delphi process to develop a classification of potential error sources in robotic-assisted spine surgery [20]. Their classification grouped errors into four broad categories: reference/navigation, patient factors, technique and equipment factors. This is more useful than attributing every discrepancy to the navigation system itself. It also provides a methodological precedent for future consensus-based refinement of the response framework proposed in this review.

Final screw position alone does not capture the complete reliability of the navigation workflow. A screw that is ultimately well positioned after repeat imaging, re-registration or conversion to another guidance technique may appear identical in an accuracy dataset to one placed without interruption. Recording the trigger for concern, the corrective action and whether the planned trajectory changed would allow successful recovery events to contribute to quality improvement rather than disappear from the denominator.

Human factors: when a coherent display is wrong

Navigation discordance may be difficult to recognise because the interface does not necessarily fail visibly. A tracked instrument can move smoothly on the display and the projected trajectory can appear plausible even when the information no longer corresponds adequately with the operative anatomy. Human-factors research describes automation bias as a tendency to over-rely on automated advice or to discount contradictory information [21]. Direct evidence quantifying automation bias in neurosurgical navigation is limited, so its frequency should not be assumed to be the same across devices or procedures.

The same literature identifies potentially relevant mitigators. Training, explicit user accountability and interface design can reduce inappropriate reliance on decision-support systems [21]. Applied to navigation, this supports a team culture in which a discrepancy raised by the surgeon, assistant, radiographer or theatre staff prompts verification rather than deference to a reassuring display. These principles inform the 'pause' and 'verify' components of the proposed sequence, although they have not been prospectively validated for neurosurgical navigation.

Augmented-reality systems may make this problem more salient because computed information is visually

colocated with the anatomy. Kos et al. found substantial variation in how augmented-reality systems in cranial neurosurgery were evaluated, including differences in registration-accuracy metrics, workflow assessment and measures of robustness [22]. Their review supports the need to evaluate alignment and system stability, but it does not establish a specific recovery strategy when an overlay becomes unreliable. Suspension of reliance on an inaccurate overlay and independent reassessment of alignment are therefore presented in this review as authors' proposed responses rather than recommendations directly tested by that review.

A navigation interruption should not automatically be treated as procedural failure. Pausing instrumentation, obtaining new imaging or converting to fluoroscopic, direct anatomical or another established form of guidance may represent an appropriate response to uncertainty. Conversely, datasets that report only completed navigated procedures can underestimate the operational consequences of systems that required correction or abandonment. Triggers for interruption, conversion rate, time to restore guidance and subsequent verification are therefore clinically relevant process measures.

Literature on training in spinal image guidance and robotics emphasises the role of operator familiarity and the learning curve rather than providing a validated troubleshooting algorithm [23]. Pivazyan et al. more directly examined the generation and propagation of error in stereotactic and computer-assisted neurosurgery, highlighting the multiple stages at which inaccuracies can enter the workflow [24]. Together with the registration, imaging, stereotactic and spine literature discussed above, these studies provide the conceptual basis for considering recognition and recovery as processes that should be evaluated separately from final technical accuracy.

Across cranial, stereotactic and spinal procedures, final technical success does not necessarily indicate that navigation remained reliable throughout the case. A tumour resection, electrode placement or screw trajectory may ultimately be satisfactory despite an earlier episode of discordance that required repeat imaging, re-registration, physiological confirmation or conversion to another guidance method. These events are clinically relevant because they describe the reliability of the navigation workflow itself, not simply the final position of the instrument or implant. Direct reporting of such interruptions remains inconsistent, which limits comparison of recovery strategies across procedures.

The proposed five-stage response framework

Figure *1* presents a five-stage conceptual response to suspected navigation discordance: detect, pause, verify, recover and document. The sequence was developed by the authors through structured synthesis of recurring principles in the registration, intraoperative imaging, stereotactic, spinal-navigation and human-factors literature [1,2,11-13,15,18-24]. None of these sources independently proposes this five-stage sequence, and the framework has not undergone Delphi consensus, prospective usability testing or clinical outcome validation.

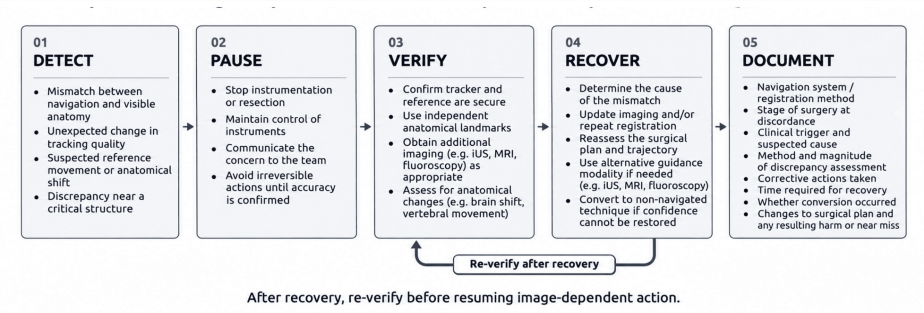


FIGURE 1: Proposed Five-Stage Response Framework for Suspected Intraoperative Neuronavigation Discordance

Conceptual five-stage response framework for suspected intraoperative neuronavigation discordance: detect, pause, verify, recover, and document. The framework was developed by the authors through structured synthesis of principles identified across literature addressing registration accuracy, intraoperative imaging, stereotactic targeting, spinal navigation, and human factors [1,2,11-13,15,18-24]. The sequence is not strictly linear; following corrective action, renewed verification is required before image-dependent activity resumes. The framework is an original conceptual synthesis and has not undergone formal expert consensus, prospective usability testing, or clinical outcome validation.

The trigger for pausing cannot currently be reduced to a single numerical error threshold. A discrepancy that is acceptable for one task may be unacceptable for another. Distance from an eloquent cortical or subcortical structure, the dimensions of a stereotactic target, the width of a pedicle, proximity to neural or vascular structures, and the reversibility of the next operative step all affect the clinical significance of an observed

disagreement. The practical trigger proposed here is therefore an unexplained discordance that could alter the safety or intended result of the next image-dependent action. The absence of validated procedure-specific thresholds remains an important area for future study.

The first action is to pause the image-dependent step while maintaining control of the instrument and communicating the concern to the operating team. This differs from a routine surgical time-out, which is performed prospectively at defined procedural stages to confirm patient, procedure and operative plans. The proposed pause is event-triggered and occurs when confidence in a previously accepted navigation relationship has changed during the operation.

Verification should seek information that is not wholly dependent on the suspected source of error. In cranial tumour surgery this may include direct microscopic anatomy, updated iUS or iMRI, or functional information where relevant. In stereotactic surgery it may include intraoperative imaging of the delivered trajectory or electrode, physiological confirmation where appropriate, and subsequent postoperative imaging. In spinal instrumentation, it may include local bony landmarks, fluoroscopy or repeat three-dimensional imaging. The choice depends on the procedure, available technology, operator experience and the consequence of proceeding incorrectly.

Recovery is not synonymous with recalibration. The team should determine whether the original image remains representative, whether registration or tracking requires correction, whether the reference has moved, whether the planned trajectory remains valid and whether anatomical change requires a new plan. If reliable guidance cannot be restored, conversion to an alternative established technique may be appropriate.

Recovery should then be followed by renewed verification before image-dependent action resumes. For this reason, the framework is not strictly linear. Figure *1* includes a feedback loop from 'Recover' to 'Verify', reflecting the need to confirm that corrective action has actually restored an acceptable relationship between guidance and the operative target.

The final stage is documentation. At minimum, the record should identify the procedure and navigation system, the registration and tracking method, the stage at which discordance was detected, the clinical trigger, the suspected failure mechanism, the magnitude and method of discrepancy assessment where measurable, the corrective action, whether conversion occurred, time required for recovery, whether the operative plan changed, and any resulting near miss or adverse event. Operator experience and the timing of detection relative to a critical procedural step may also be relevant. Recording these events would allow future studies to examine the reliability of the complete navigation workflow rather than only the final accuracy of successfully completed cases.

Limits of the proposed framework

This review brings together evidence from procedures with different anatomy, technology and risk. Cranial brain deformation is not mechanically equivalent to spinal reference displacement, and neither should be used as a proxy for stereotactic targeting error. The proposed sequence therefore unifies the response to suspected unreliable guidance rather than the underlying failure mechanism or technical correction.

The framework remains conceptual. It has not undergone formal expert consensus, Delphi validation, prospective usability testing or evaluation against patient-level safety outcomes. It should therefore not be interpreted as a clinical decision rule or as evidence that a specific recovery sequence reduces neurological or procedural complications. Local resources also affect what constitutes a feasible recovery strategy. Intraoperative MRI is not universally available, while ultrasound, alternative navigation workflows and conversion to another guidance modality depend on equipment, training and operator experience.

The literature used for this narrative review was selected purposively to address registration mechanics, intraoperative imaging, stereotactic targeting, spinal navigation, human factors and recovery processes. This approach supports cross-procedure conceptual synthesis but introduces selection bias and cannot establish the incidence of navigation failure or determine which corrective strategy is superior. Direct evidence describing navigation interruptions, failed guidance and recovery processes remains limited in several areas, particularly stereotactic and spinal procedures. This should be regarded as an evidence gap rather than evidence that recovery strategies are ineffective.

Future research and evaluation of navigation recovery

Current evaluation of image-guided neurosurgery commonly focuses on TRE, instrument-tip accuracy, extent of tumour resection, electrode-placement error or final pedicle screw position. These measures remain important but do not describe how reliably a team recognises and responds to emerging navigation discordance. Future studies should therefore report both final technical accuracy and the process by which unreliable guidance was detected, verified and corrected.

A minimum evaluation should include the total number of image-guided tasks attempted, the number in

which navigation was interrupted or abandoned, the trigger for concern, the stage of the procedure at which discordance was detected, the method used for independent verification, the corrective action taken, the time required to restore confidence, whether conversion to an alternative technique was necessary, and whether the planned operative trajectory or target changed. The magnitude of the discrepancy, where it can be measured, and any associated near miss or adverse event should also be recorded.

Evaluation can proceed in stages. Simulation studies can test whether surgeons and theatre teams recognise reference motion, inaccurate overlays, segmentation errors or misleading tracking information. Phantom and cadaveric studies can then quantify the relationship between true spatial error, displayed system confidence and the effectiveness of corrective actions. Prospective clinical registries could subsequently document real navigation interruptions, corrected trajectories, conversions and downstream outcomes without deliberately exposing patients to unsafe conditions.

The development and validation of the proposed framework could follow principles used in the evaluation of surgical innovation. Initial refinement through structured expert consensus, including a Delphi process similar to that used for classification of robotic spine-surgery errors [20], could establish whether the proposed stages and reporting variables have face and content validity. Subsequent prospective usability testing could examine whether the framework is practical during simulated and clinical workflows. Broader multicentre evaluation would then be required before any claim could be made regarding reliability, workflow benefit or patient safety. This staged approach is consistent with the broader principle underlying IDEAL that surgical innovations should progress from development and refinement to structured prospective evaluation before widespread adoption [25].

Claims of clinical benefit should remain separate from technical correction. Even when updated intraoperative imaging improves gross-total resection, the independent effect of correcting a registration discrepancy cannot be separated easily from the effects of repeat imaging, surgeon decision-making, operative timing and case selection [5-9]. Demonstrating that navigation recovery improves patient outcomes would require prespecified definitions of discordance, transparent denominator accounting, clinically relevant outcome measures and comparison with an appropriate contemporary workflow. Procedure-specific examples of navigation discordance, independent verification and potential recovery strategies are summarised in Table *1*.

Operative context	Likely source of discordance	Independent verification	Potential recovery strategy
Cranial tumour resection	Brain deformation following dural opening, cerebrospinal-fluid loss, swelling, retraction or tissue resection	Direct anatomical assessment, intraoperative ultrasound, functional mapping, or updated MRI where available	Repeat intraoperative ultrasound or MRI, re-registration where appropriate, or modification of the operative plan [10-14]
Stereotactic targeting	Imaging distortion, registration error, target-definition error, or mechanical trajectory deviation	Intraoperative CT or MRI, physiological confirmation where appropriate, and postoperative imaging of electrode position	Reassess target and trajectory, verify registration and mechanical guidance, and reposition the electrode or trajectory if verification demonstrates unacceptable deviation [2,15-17,24]
Spinal instrumentation	Reference-array displacement, changes in vertebral position, registration error, or trajectory deviation	Local bony landmarks, fluoroscopy, or repeat three-dimensional imaging	Repeat image acquisition, re-register the target level, reassess the trajectory, or convert to an alternative established guidance technique [18-20]
Augmented-reality navigation	Overlay drift, tracking inconsistency, registration failure, or loss of correspondence between the virtual overlay and operative anatomy	Comparison of the overlay with directly visible anatomy and, where appropriate, independent imaging	Authors' proposed response: suspend reliance on the overlay, independently reassess alignment, and resume augmented-reality guidance only after satisfactory correspondence has been re-established [22]

TABLE 1: Navigation Discordance, Verification, and Potential Recovery Strategies by Operative Context

Comparison of potential sources of navigation discordance, independent verification methods, and potential recovery strategies across cranial tumour surgery, stereotactic targeting, spinal instrumentation, and augmented-reality-assisted navigation. The table represents an original synthesis of the literature discussed in this review [2,10-20,22,24]. Where a specific recovery strategy has not been directly evaluated, it is presented as an authors' proposed response rather than a validated recommendation. The approaches shown are not intended to constitute a clinical decision rule.

CT: computed tomography; MRI: magnetic resonance imaging

The proposed minimum reporting dataset for intraoperative navigation discordance and recovery is summarised in Table *2*.

Domain	Suggested field	Rationale
Procedure and system	Procedure type, anatomical target, navigation platform, tracking technology, and guidance modality	Defines the operative and technological context in which discordance occurred
Registration	Registration method and reference-frame configuration	Allows comparison of failure mechanisms across point-based, surface-based, automatic, optical, electromagnetic, and other workflows
Exposure	Total number of image-guided tasks attempted	Prevents exclusion of failed, interrupted, or converted procedures from accuracy denominators
Detection	Trigger for suspected navigation discordance, stage of surgery, and timing relative to a critical operative step	Establishes when and how loss of confidence became clinically relevant
Discordance	Operational definition, suspected source, and measured magnitude of discrepancy where available	Distinguishes subjective concern from quantifiable spatial or technical error
Verification	Independent imaging modality, anatomical landmark, physiological confirmation, or other method used	Records how suspected discordance was assessed independently of the original guidance system
Response	Pausing instrumentation, repeating imaging or registration, modifying the trajectory, repositioning an implant or electrode, or switching guidance modality	Characterises the corrective strategy used
Workflow	Time required for verification and recovery, whether conversion was necessary, and whether the procedure was delayed or abandoned	Quantifies the operational consequences of the navigation interruption
Operator factors	Primary operator experience and relevant navigation-system experience	Allows assessment of whether recognition and recovery vary with familiarity or learning curve
Consequence	Change to the operative plan, near miss, adverse event, complication, or absence of harm, with severity classification where applicable	Links technical and workflow events to clinically relevant consequences

TABLE 2: Proposed Minimum Reporting Dataset for Intraoperative Navigation Discordance and Recovery

Proposed minimum reporting dataset for intraoperative navigation discordance and recovery. The suggested variables capture procedural and technological context, registration method, task exposure, detection, magnitude of discordance, independent verification, corrective response, workflow consequences, operator experience, and patient-related outcomes. The dataset was developed through an original synthesis of literature concerning navigation accuracy, error classification, human factors, stereotactic and spinal navigation, and procedural recovery [1,2,15,18-24]. It has not undergone formal consensus development or prospective clinical validation. Future refinement could use structured expert consensus followed by staged prospective evaluation in keeping with principles used for assessment of surgical innovation [25].

Conclusions

Neuronavigation is an important component of contemporary cranial, stereotactic and spinal neurosurgery, but its reliability depends on the continued validity of image registration, anatomical correspondence, tracking and trajectory information. A technically precise system may still provide misleading guidance when anatomy changes, a reference moves or the assumptions underlying registration are no longer valid. Recognising navigation discordance and verifying it independently are therefore central to safe use of image-guided surgery. This review proposes a five-stage response framework comprising detection, pausing image-dependent action, independent verification, recovery and documentation. The framework is intended to provide a structured way of thinking about suspected navigation discordance across different neurosurgical procedures. It remains conceptual and has not undergone formal consensus development, prospective usability testing or clinical outcome validation.

Future research should evaluate not only final technical accuracy but also how often navigation is interrupted, how discordance is recognised, which corrective strategies are used, how long recovery takes, whether conversion is required and whether the operative plan changes. Simulation studies, structured expert consensus, prospective registries and multicentre evaluation could help determine whether the proposed framework is practical and reproducible. Until such validation is available, it should be regarded as a framework for reporting, discussion and future study rather than a standardised clinical algorithm.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Disclosures

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