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Research article

CyPVICS: A framework to prevent or minimise cybersickness in immersive virtual clinical simulation

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A R T I C L E I N F O

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A B S T R A C T

Cybersickness is a global issue affecting users of immersive virtual reality. However, there is no agreement on the exact cause of cybersickness. Taking into consideration how it can differ greatly from one person to another, it makes it even more difficult to determine the exact cause or find a solution. Because cybersickness excludes so many prospective users, including healthcare professionals, from using immersive virtual reality as a learning tool, this research sought to find solutions in existing literature and construct a framework that can be used to **p**revent or minimise **cy**bersickness during **i**mmersive **v**irtual **c**linical **s**imulation (CyPVICS). The Bestfit Framework by Carrol and authors were used to construct the CyPVICS framework. The process started by conducting two separate literature searchers using the BeHEMoTh (for models, theories, and frameworks) and SPIDER (for primary research articles) search techniques. Once the literature searches were completed the models, theories and framework were used to construct a priori framework. The models' theories and frameworks were analysed to determine aspects relevant to causes, reducing, eliminating, and detecting cybersickness. The priori framework was expanded by, first coding the findings of the primary research study into the existing aspects of the priori framework. Once coded the aspects that could not be coded were added in the relevant category, for example causes. After reviewing 1567 abstracts and titles as part of the BeHEMoTh search string,19 full text articles, a total of 15 papers containing models, theories, and frameworks, were used to construct the initial CyPVICS framework. Once the initial CyPVICS was created, a total 904 primary research studies (SPIDER) were evaluated, based on their titles and abstracts, of which 100 were reviewed in full text. In total, 67 articles were accepted and coded to expand the initial CyPVICS framework. This paper presents the CyPVICS framework for use, not only in health professions' education, but also in other disciplines, since the incorporated models, theories, frameworks, and primary research studies were not specific to virtual clinical simulation.

1. Introduction

Cybersickness (CS) is one of the most significant issues associated with the use of immersive virtual reality (VR). Common symptoms of CS include nausea, pale skin, vomiting, dizziness, and headaches. CS is similar to motion sickness as there are many similar symptoms, but they often differ from person to person [1]. The exact causes of CS have not yet been established however, there are various theories as to why someone might experience it, for example the poison theory, postural instability theory, rest frame

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theory, and sensory conflict/mismatch theory. It is believed that the most common causes of CS relate to the sensory conflict/mismatch theory, which suggests that CS is a result of the differences between the perceived sense while immersed in a virtual environment (VE) and the actual environment, for example, moving in the virtual environment while remaining stationary in the physical environment [1–3].

CS excludes many prospective users from using immersive VR. As pointed out by Botha, De Wet and Botma [4], the consequence of the CS problem for nursing students who participated in their study, and who consequently experienced CS, was that they could potentially be excluded from using immersive VR as a learning tool to improve their theoretical and practical integration. Immersive VR is usually referred to as immersive virtual clinical simulation (VCS) in the health care context and will be the preferred term hence forth. While searching for ways to prevent or minimise CS in immersive VCS, it became apparent that no specific framework existed to assist in preventing or minimising CS. The aim of this study then was to create a framework, using the best fit framework by Carroll, Booths, Leaviss and Rick [5], that can be used to prevent or minimise CS in immersive VCS. The name, CyPVICS was chosen due to its lack of relation to an existing item, name or object and it was derived by using and rearranging letters in the full name. The framework is known as the framework to **p**revent or minimise **cy**bersickness during **i**mmersive **v**irtual **c**linical **s**imulation (CyPVICS). This manuscript starts by providing the methods and materials used to construct the CyPVICS framework, the methods and materials lead out into the results of the two search strings (BeHEMoTh and SPIDER). The CyPVICS framework is then presented along with the different aspects it consists of, before concluding the endeavour.

2. Methods and materials

Using the best fit framework by Carroll, Booth, Leaviss, & Rick [5], the CyPVICS framework was constructed for this study. The best fit framework consists of various stages. In this research project, the first two stages ran simultaneously. The first step included identifying relevant frameworks, conceptual models or theory publications, using the BeHEMoTh (interest (Be), health context (H), exclusions (E) and models or theories (MoTh)) approach. The second stage involved identifying relevant research studies with qualitative or quantitative evidence, using the SPIDER (setting/population (S), the phenomenon of interest (PI), the design (D), evaluation (E) and the research type (R)) technique [5].

The research question that was used to determine the relevant term for both the BeHEMoTh and the SPIDER techniques was: "*Which determinants should form part of a framework for designing immersive virtual clinical simulations to prevent or minimise cybersickness?*"

Although the main research question was the same for both the BeHEMoTh and SPIDER techniques, the way in which the search terms were extracted from the main question, differed for these two techniques.

From the main research question, the first term identified to be used in both the BeHEMoTh and the SPIDER techniques was *immersive virtual clinical simulation*, as it represented the application area of this study. The second term was *cybersickness,* as it was the phenomenon in question for this study. The third term was *determinants*, which related to either models' theories or frameworks

Table 1
Search terms and synonyms for BeHEMoTH and SPIDER techniques.

Question Extract and Applicable Technique	Search Terms
Immersive Virtual clinical simulation (SIPDER and BeHEMoTh)	• **Virtual clinical simulation (VCS)** [6] • **Virtual Reality Simulation (VRS)** [7,8] • **Virtual Simulation (VS)** [9] • **Clinical Virtual Simulation (CVS)** [10] • **active HMD-based virtual reality** [11] • **virtual reality experiences with head-mounted displays** [12] • **Virtual Reality** [13] • **HMD-based virtual reality** [14] • **immersive content** [15] • **VR simulation** [16]
Cybersickness (SIPDER and BeHEMoTh)	• **Cybersickness (CS)** [3,17] • **Virtual reality induced motion sickness (VRIMS)** [18] • **Virtual reality induced symptoms and effect (VRISE)** [19] • **Visually induced motion sickness (VIMS)** [3,17] • **Simulator Sickness** [20] • **Motion Sickness** [21] • **Virtual Reality Sickness** [22]
Determinants/Aspects (SPIDER) ***All terms relate to well know methods and techniques in primary research studies***	• **Quantitative** • **Qualitative** • **Mixed method** • **Case Study** • **Interview** • **Views** • **Attitudes** • **Focus group** • **Experiment** • **Opinions**
Determinants/Constructs (BeHEMoTh)	• **Models, Theories, Frameworks** [5]

(BeHEMoTh) or primary research (SPIDER). For all the terms, synonyms were also sourced from literature to obtain the best possible results and to include as much literature sources as possible (see Table 1).

Once the applicable terms and synonyms were identified, the technique-specific approach could follow. To reduce bias and improve validity, the search terms were compiled by the researchers and sent to an information specialist to search available databases for relevant literature [23]. The following databases were searched for the literature: Academic Search Ultimate, Scopus, WoS, Africa-Wide Information, APA PsycArticles, APA PsycInfo, CAB Abstracts, CINAHL with Full Text, ERIC, GreenFILE, Health Source - Consumer Edition, Health Source: Nursing/Academic Edition, Humanities Source Ultimate, MEDLINE, OpenDissertations, SPORTDiscus with Full Text.

Both the BeHEMoTh and SPIDER searches had no date delimiter. The initial search was up to October of 2021, after which two additional searches were conducted to include additional databases and to check for new or additional literature to support the CyPVICS framework. The last two literature searches were combined with the previous search and ran up until December 2023. The initial process of abstract review between various academics and incorporation took part from beginning of 2020 to October 2022. For the remaining two searched the same processes were followed, however due to the coding already being done it was easier to code new literature to the framework.

The abstracts of articles were separately screened for the BeHEMoTh and SPIDER by four reviewers to limit bias and increase validity [24]. The researchers sourced the full text articles, and two reviewers evaluated them for inclusion into the CyPVICS framework. The abstracts and full text articles were checked based on the inclusion criteria set out in Table 3s (BeHEMoTh) and Table 4 (SPIDER), while abstracts that did not conform to this criteria were excluded. For both the abstracts and the full text articles a meeting was scheduled to discuss the articles that all reviewers did not agree on, to reach consensus on what will be included in the CyPVICS framework. Once done, only the main researcher analysed and extracted data from the full text documents to facilitate consistency.

2.1. BeHEMoTh search string

The BeHEMoTh assisted in identifying relevant frameworks, theories and models which were reduced to key elements and used as themes in the CyPVICS framework. The themes were coded by extracting relevant key areas applicable in to CS, which included causes of CS, methods to reduce, prevent or minimise CS and any links that indicated the relevance of CS to other aspects of VR, for example the link to presence and realism. For the BeHEMoTh, two separate searches were done to obtain literature on models, theories or frameworks. Both search strings had no date delimiter. The first search string for the BeHEMoTh technique was ((Be **AND** H **AND** MoTh) **NOT** E) and can be seen in Table 2.

From this search string only six results were found, of which none focused on a model, theory or framework. Due to the lack in literature in the health or VCS context, the search string was broadened by reducing it to (**Be** and **MoTh**), as can be seen in Table 3 (also used as inclusion criteria). The new search string resulted in finding more models, theories and frameworks, although they were not necessarily in a VCS context. Even though these models, theories or frameworks were from different disciplines, CS was still applicable here. Consequently, they were evaluated for possible inclusion into the CyPVICS framework.

The following section depicts the SPIDER search sting, which ran concurrently with the BeHEMoTh search string.

2.2. SPIDER search string

The SPIDER technique was used to find primary research studies without a date delimiter. The search strategy for the SPIDER technique (S **AND** PI **AND** DER) and the search string (also used as inclusion criteria) can be seen in Table 4.

Extracts from primary research articles were added to themes identified during the BeHEMoTh analysis. The main goal of the SPIDER was to reinforce the models' theories and frameworks and add new possible links, causes of CS and methods to minimise, prevent, or detect CS. To do this a deductive analysis was done to include the results from the SPIDER search, which could not be coded against the CyPVICS framework. The newly identified themes were added to the CyPVICS framework to produce a new version. The new CyPVICS framework was subsequently analysed to explore relationships between themes. Related themes were then grouped together [5]. The groupings were done based on the research sharing common overlapping theories, models or frameworks and they were named accordingly, for example movement associated causes were grouped together.

Table 2
First BeHEMoTh search string used for this study.

First BeHEMoTh search string	
Be	Cybersickness OR Virtual reality induced motion sickness OR Virtual reality induced symptoms and effect OR Visually induced motion sickness OR Simulator Sickness OR Motion Sickness OR Virtual Reality Sickness
AND	
H	Virtual clinical simulation OR Virtual Reality Simulation OR Virtual Simulation OR Clinical Virtual Simulation OR active HMD-based virtual reality OR virtual reality experiences with head-mounted displays OR Virtual Reality OR HMD-based virtual reality OR immersive content OR VR simulation
AND	
MoTh	Model OR Theory OR Framework
NOT	
E	Case Study OR Interview OR Views OR Attitudes OR Focus group OR Experiment OR Opinions OR Animal Model

Table 3
Broadened search string for BeHEMoTh and inclusion criteria.

Second BeHEMoTh search string	
Be	Cybersickness **OR** Virtual reality induced motion sickness **OR** Virtual reality induced symptoms and effect **OR** Visually induced motion sickness **OR** Simulator Sickness **OR** Motion Sickness **OR** Virtual Reality Sickness
AND	
MoTh	Model OR Theory OR Framework

Table 4
SPIDER search string and inclusion criteria.

SPIDER search string	
S	Virtual clinical simulation **OR** Virtual Reality Simulation **OR** Virtual Simulation **OR** Clinical Virtual Simulation **OR** active HMD-based virtual reality **OR** virtual reality experiences with head-mounted displays **OR** Virtual Reality **OR** HMD-based virtual reality **OR** immersive content **OR** VR simulation
AND	
PI	Cybersickness **OR** Virtual reality induced motion sickness **OR** Virtual reality induced symptoms and effect **OR** Visually induced motion sickness **OR** Simulator Sickness **OR** Motion Sickness **OR** Virtual Reality Sickness
AND	
DER	Quantitative **OR** Qualitative **OR** Mixed method **OR** Case Study **OR** Interview **OR** Views **OR** Attitudes **OR** Focus group **OR** Experiment **OR** Opinions

3. Results

3.1. Existing models, theories or frameworks (BeHEMoTh)

From the broadened BeHEMoTh search string (Table 3), a total of 1567 results were obtained after automatic deduplication from the older and newer search. Once the search was completed, all the abstracts and titles were evaluated to determine whether they conformed to the criteria in Table 3.

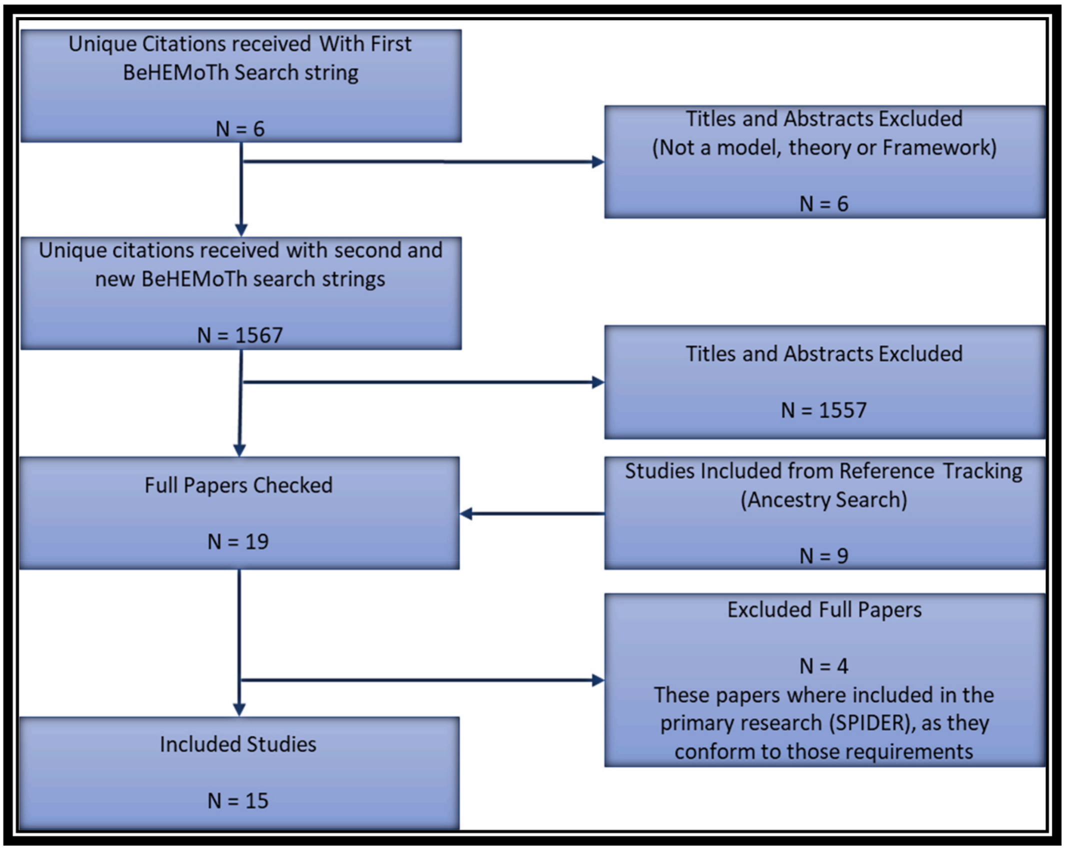

Fig. 1. PRISMA Flow Chart, applicable to the BeHEMoTh technique.

During the process of abstract and title evaluation, a total of 1557 titles and abstracts were excluded due to not being applicable to the terms identified for the BeHEMoTh technique. From the 10 papers, references were analysed to determine whether there were more articles that could be included as part of the ancestry search. After the ancestry search, a total of nine titles and abstracts were included, which brought the total full text articles that had to be reviewed for inclusion in the CyPVICS framework to 19. After review, 15 studies were included, and even though none of them were applicable to CS in VCS, they were still used as a starting point for creating the CyPVICS framework. The process as described above, is diagrammatically presented in the Prisma flow chart in Fig. 1 and includes both searches previously mentioned.

From the 15 models, theories or frameworks that were incorporated in the construction of the initial CyPVICS Framework, it is important to note that the models, theories, and frameworks presented here are not exclusively linked to VCS. However, even if not directly related to VCS, they were still included, as they provided invaluable insight into possible solutions to counteract CS. Rather than constructing a completely new framework from scratch, the CyPVICS Framework was systematically constructed from applicable diagrams or parts of diagrams from these existing models, theories, and frameworks. Set out in Table 5 are the aspects taken from them.

Once the models, theories and frameworks were coded, the initial CyPVICS Framework could be compiled. With the initial CyPVICS Framework in place, the coding of the primary research articles could proceed. In the following section, the primary research studies

Table 5
Models, Theories and Frameworks with CyPVICS Incorporated aspects.

Existing Model, Theory or Framework	Aspects taken from the primary Models, Theories or Frameworks (BeHEMoTh)
Framework for Virtual Environments (FIVE) [25]	• The first aspect was *presence*, as it coincides with other models that were used to construct this initial framework. • The second aspect taken from FIVE was *models of interaction*, as there might be new ways of interacting with VEs which might assist in reducing CS. • The third useful component taken from the FIVE was the *system/software* and the *VE kernel*, as good design and/or software engineering principles are also key to reduce the onset of CS. • The fourth component links to the VE kernel and software and includes the *objects' physics and behaviour*. • The fifth and final included aspect was the *sensors*. They were included, as sensors form part of possible methods to detect the onset of CS and to possibly implement automatic measures to reduce the effects of CS.
Closed Loop Framework for Detecting CS: CyberSense [26]	• CyberSence provides a non-disruptive means to manage the onset of CS during user navigation in immersive VR and, therefore, was included as a CS detection and reduction method in the CyPVICS Framework
Cybersickness Estimation Model (CSEM) [27]	• The entire CSEM was added to the CyPVICS Framework as a possible method for detecting CS during immersive VR navigation. This could assist the facilitator to stop the session in a case where a participant started showing signs and symptoms of CS.
Neural Mismatch Model [28]	• From the Neural Mismatch Model, the Sensory Conflict/Mismatch Theory was sourced and included as a cause of CS. The rest of the Neural Mismatch Model was included as part of the FIVE sensors.
Computational Model of Motion Sickness [29]	• From the Computational Model of Motion Sickness, the Sensory Conflict/Mismatch Theory was, once again, identified as a possible cause of CS. The model itself linked to a method for predicting CS before its onset and was included as such.
Creativity and User Experience Model (CRUX) [30]	• From the CRUX Model, the aspect of UX was taken as a possible method to reduce CS For example, if the VE was rigorously tested by means of tried and tested usability and UX methods, it should assist in reducing the effect of CS and stress, while increasing novelty, flow, and positive emotions.
Structural Model: Relationship of Control, Cybersickness and Prescence [31] **This model was not named* per *the authors, and only referred to as a structural model*	• From this Structural Model, various aspects such as the relationships between CS, presence and workload, were taken and added to the CyPVICS Framework. The purpose was to showcase the effect that each aspect has on another. • Another aspect taken from this Structural Model was that of increased workload as a possible cause of CS. • The actual and perceived time was not included due to time not complementing the goal of the CyPVICS Framework.
Sensory Conflict/Mismatch Theory [32]	• Seeing how the Sensory Conflict/Mismatch Theory is such a widely known phenomenon in causing CS, it was added as a possible cause of CS.
Poison Theory [33]	• The poison theory, was excluded due to the wide criticism and the fact that no support in recent literature could be found for this theory
Postural Instability Theory [34]	• The Postural Instability Theory is still a commonly referred to phenomenon that causes CS and was, therefore, included as a possible CS cause in the CyPVICS Framework.
Rest Frame Theory [35]	• There were contradicting cases where providing a rest frame did not reduce the effects of CS. This indicated that a rest frame might assist some users, but not all of them. It was, therefore, still included as a possible cause of CS seeing that the theory revolves around the lack of a rest frame being a cause of CS.
Vertical Mismatch Theory [36]	• Even though the theory is not as widely known and accepted, it has links to the Sensory Conflict/ Mismatch Theory and was, therefore, added as a possible cause of CS
Virtual Reality Sickness Predictor (VRSP) Framework [37]	• The VRSP proved to be a useful framework in predicting the onset of cybersickness, it was therefore added as part of possible methods to detect the onset of CS.
Deep Learning based Framework [38]	• The Deep Learning based framework aims to detect CS by means of deep learning algorithms, for this reason it was added as part of possible methods to detect the onset of CS.
TruVR: a framework to develop a trustworthy CS detection technique [39]	• TruVR uses machine learning to determine the onset of CS and was added as an early CS detection method

that were included from the SPIDER technique, will be presented.

3.2. Primary research studies (SPIDER)

From the SPIDER technique (Table 4), a total of 904 results were obtained after automatic deduplication. Once the search was completed, all the abstracts and titles were evaluated to determine whether they conformed to the research question from which the SPIDER technique search terms were derived.

During the process of abstract and title evaluation, a total of 804 titles and abstracts were excluded due to them not being applicable to the terms identified for the SPIDER technique. Once the abstract and title evaluations where completed, the full papers were sourced and analysed to determine their eligibility. From the 87 papers, references were analysed to determine whether there were articles which could be included as part of the ancestry search. After the ancestry search was conducted, a total of 13 titles and abstracts were included. This brought the article count to 100 full text articles that were reviewed for possible inclusion as primary research studies. In total, 67 studies conformed to the requirements of the terms identified for the SPIDER technique. The process as described above, is presented in the Prisma flow chart in Fig. 2.

For the primary research studies for the SPIDER technique, the situation was the same as for the BeHEMoTh, as not all 67 studies included focused on immersive VR or immersive VCS. However, they were still included based on their association to possible CS solutions. From the data extracted from the SPIDER primary research studies, Table 6 was constructed to provide an overview of the CS causes that could form part of the CyPVICS Framework.

4. Discussion: CyPVICS framework

The CyPVICS framework as described below, is graphically represented in Fig. 4. The CyPVICS Framework shows that a higher sense of presence improves a participant's experience of immersive VCS. However, while higher realism increases presence, it also increases CS. In the literature, there are multiple theories as to what causes CS and possible ways to minimise or prevent this phenomenon. However, a concrete theory with a long-term solution is still not available. Within the CyPVICS Framework, there are three main categories, namely the causes of CS, followed by methods to prevent or minimise CS, and lastly, the associated minimisation or prevention techniques.

The causes refer to known causes that could be found in the literature, where the possible reasoning as to why a person might experience CS while using immersive VCS, is described. These causes were grouped based on shared methods to prevent or minimise CS, and include momentum associated causes (Sensory Conflict/Mismatch Theory, Postural Instability Theory and Vertical Mismatch Theory), the development and usability causes (severe framerate fluctuations, low VE/system usability, varying latency, rotational movement, and acceleration), increased workload, and finally the Rest Frame Theory.

Next to the causes on the CyPVICS Framework, the methods (broad categories of interventions) for the prevention or minimisation of CS during immersive VCS, are shown. As with the causes, the methods were categorised based on their overlapping causes. The first

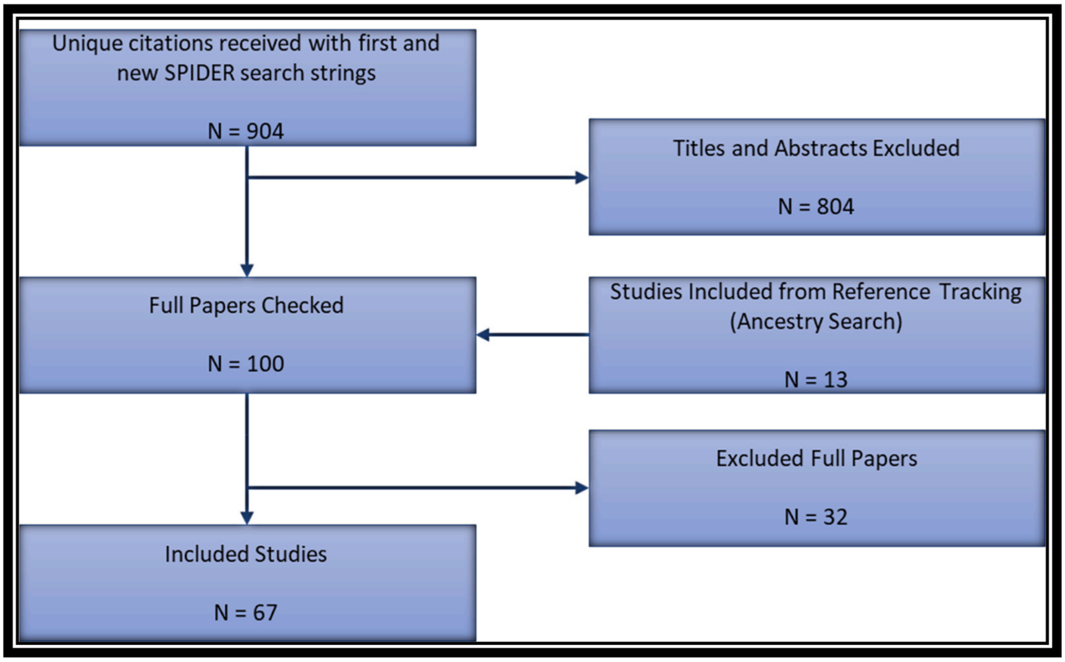

Fig. 2. PRISMA Flow Chart, applicable to the SPIDER technique used for this study.

Table 6
Inductive analysis of primary research studies and coding to the CyPVICS Framework.

Associated Theme/Sub-theme	Aspects taken from the primary research studies (SPIDER)
Link between presence, realism, and CS	• Higher level of visual realism and presence induces a higher level of CS and vice versa [12] • Level of CS increases as the level of immersion/presence increases [40]
Causes of CS	• Sensory Conflict/Mismatch Theory [41–46]; • Rotational Movements increase CS [19,47] • Postural Instability [46,48–50] • Postural sway/Instability [51] • Insomnia [52] • Display Lag [43,53] • Severe Framerate fluctuations [54] • Rest Frame Theory (static or dynamic visual guide) [49,55–58] • Low VE/System Usability [59] • Subjective Vertical Mismatch (SVM) Theory [14,53] • Acceleration [47] • Ocular Refraction Disorder [60] • Display resolution [60] • Screen refresh rate [61] • Workload [62]
Methods of Prevention or Minimisation	• Adaption Training [63,64] • Habituation (repeated exposure) [64–67] • Predictive latency compensation [41] • Diaphragmatic breathing [68,69] • Relaxing music [70] • Airflow [71,72] • Noisy vestibular stimulation through bone-vibration [73] • Narrative context [74] • Non-invasive Galvanic vestibular stimulation (GVS) [44,75] • Visual vestibular synchronised conditions [45] • Applying in game Visual Guide (crosshair, nose or MSP) [55,56,58,62] • Reducing global stereopsis [76] • Chewing gum [77] • Using a combination of motion cues and visual cues [78] • Oculomotor exercises [79] • Distracting users (Auditory [80], Visual or Cognitive Distractions) [81] • Galvanic cutaneous stimulation [80]
Associated Prevention or Minimisation Techniques (linked to Improved Models of Interaction)	• Virtual Reality Navigation Chair (VRNChair) [82,83] • March/Walk in place [84] • Jog in place [85] • Tilt chair with neck brace; Omni Directional Treadmill (In female participants) [83] • Joystick and Teleportation [59] • Omni directional treadmill (ODT) increase the user experience but did not decrease CS [86] • Teleportation [87]
Associated Prevention or Minimisation Techniques (linked to Software/System Design)	• Controlling the field of view within the HMD [88,89] • Visual flow direction delays the onset of CS (Moving backwards vs forward) [90] • Head lock and Neckbrace [19] • Rotation blurring [91] • Field of View (fov) restriction [62,92–95] • Saliency detection with dynamic non salient blurring [96,97] • Spatial blur [62,98] • Using a dynamic field of view [93,99] • CS can be reduced if usability and UX testing is done; Best design principles are incorporated from the start of product design [87]
Associated Prevention or Minimisation Techniques (linked to Early CS Detection)	• HMD inertial measurement unit (IMU) [42] • Balance Board [51]; • Deep motion sickness predictor [100] • CS can be predicted using eye movement measurements [14] • Sensors [50,101–103] • Deep Simulator Sickness Estimation Method [104]

Incorporating the primary research studies, produced the final CyPVICS Framework.

method to prevent or minimise CS during VCS was improved models of interaction, followed by predictive latency compensation, habituation/adaption training, non-invasive galvanic vestibular stimulation, noisy vestibular stimulation through bone vibration, Galvanic cutaneous stimulation, visual vestibular synchronised conditions and reducing global stereopsis. The associated reduction/minimisation techniques house the usability and user experience (UX) methods, along with the software/system design methods, followed by decreasing the workload and applying an in-game visual guide, such as a crosshair. The early detection methods that could be used to detect CS before it manifests (to be subsequently able to apply the appropriate intervention to prevent or minimise CS), are listed next (methods of preventing or minimising CS without causes). Finally, for some methods, no links could be found in the literature as to their causes. They were, therefore, classified as "Methods of preventing or minimising CS without causes or techniques". These include airflow, diaphragmatic breathing, narrative context, relaxing music, headlock and neck brace, chewing gum and motion cues with visual cues, oculomotor exercises and distracting users.

The third category on the CyPVICS Framework (to the right of the methods of CS prevention or minimisation), houses the techniques associated with each method group to minimise or prevent CS. There is no direct relationship between the associated minimisation or prevention techniques since they house sub-themes of the methods to prevent of minimise CS. The first technique specifically pertains to the improved models of interaction and contrasts various models of interacting within VCS, for example, using teleporting vs free move or using an omnidirectional treadmill (ODT). The next group of associated techniques are linked to the usability and UX and software/system design methods, and entails the use of usability and UX testing, best practices, rotation blurring, field of view restrictions, reversed visual flow direction, spatial blur, saliency detection with dynamic non-salient blurring, constant latency display resolution and screen refresh rate. The last linked techniques are the different methods/models for detecting CS before it becomes an issue, namely the CyberSense framework, Sensors, CSEM, HMD inertial measurement unit (IMU), Balance Board, Deep motion sickness predictor, eye movement measurements, Computational Model of Motion Sickness, Virtual Reality Sickness Predictor (VRSP), Deep Learning Based Framework, TruVR framework and the Deep Simulator Sickness Estimation Method.

From a bird's eye view, the CyPVICS Framework in Fig. 3 shows the progression of CS, starting from the increased presence in VCS and higher realism, to the causes of CS, known prevention or minimisation methods, and their associated techniques. Once CS has been minimised or prevented, the user should experience a higher sense of presence and realism. However, literature indicates that a higher sense of presence and realism often leads to higher levels of CS. It finally highlights the complexity of CS - as soon as one issue (CS cause) is addressed, another issue might appear. As an example: just as the participant might find that the navigation technique eased the CS experience, he/she might suddenly experience CS from varying latency from another immersive VR game or platform.

In the following sections, the components of the CyPVICS Framework are discussed, starting with CS, presence, and realism in VCS.

4.1. Cybersickness, presence and realism

The first part of the CyPVICS Framework in Fig. 3 forms the link between CS, presence in VCS, and realism, as can be seen in Fig. 4. Presence is the state of consciousness of the participant during immersion in a VE [25]. On the other hand, CS is a phenomenon where the participant experiences symptoms similar to that of motion sickness, for example, nausea and dizziness [1,105]. The link between CS and VCS presence was obtained from the Structural Model: Relationship of Control, Cybersickness and Prescence [31], and

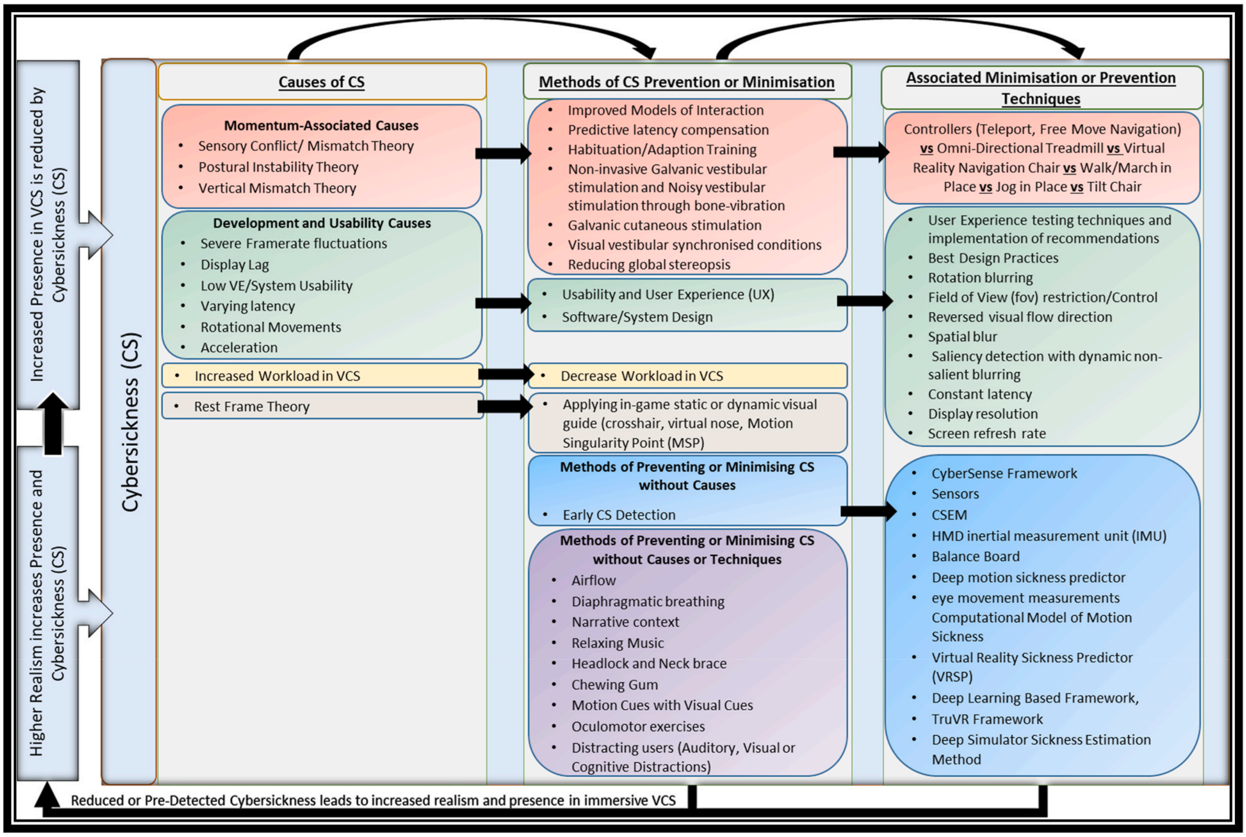

Fig. 3. Final CyPVICS framework **(colour print)**.

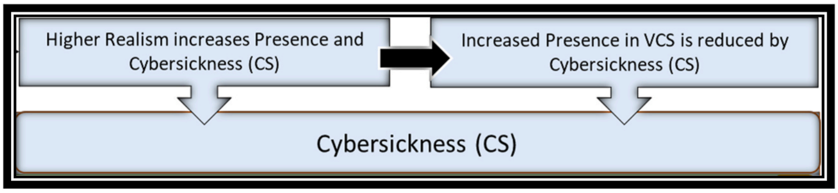

Fig. 4. Current section of CyPVICS Framework being discussed (CS, Presence and Realism (extreme left of Fig. 4)) **(Colour Print)**.

indicates that CS decreases the presence that a participant will experience while immersed in a VCS.

The link between realism and CS was obtained from Arttu [12] who indicated that the higher the realism of the VCS, the higher the CS that a participant will experience. However, higher realism of the VCS also increases the participant's presence in the VCS [31]. The ideal situation is where a participant has a high sense of presence with a low level of CS. However, the links show that a higher sense of realism leads to higher levels of CS, which in turn decreases the participant's presence.

4.2. Causes of CS with methods and techniques

In the following sections, the causes of CS, with their associated methods and techniques for preventing or minimising CS, will be discussed. The momentum-associated causes (Sensory Conflict/Mismatch Theory, Postural Instability Theory and Vertical Mismatch Theory) will be discussed first.

4.2.1. Momentum-associated causes

While constructing the CyPVICS Framework, it became apparent that there were overlapping reduction methods and techniques for some of the theories. Therefore, they were grouped together under the heading 'Momentum-Associated Causes' (Fig. 5).

The Sensory Conflict/Mismatch Theory, Postural Instability Theory and Vertical Mismatch Theory were added as known causes of CS [34,36,46,49,53] under the heading of momentum associated causes.

The most well-known CS theory is the Sensory Conflict/Mismatch Theory (also referred to as the Sensory Mismatch Theory), which suggests that CS results from sensory conflict/mismatch and refers to the imbalance between the sensory systems used in the perception of motion. The theory argues that CS occurs when the human brain receives incoherent or no stimuli via the visual and vestibular systems [32]. An example would be when the user moves around in the VE but remains in a stationary position in the physical world and is known as *vection* and has been argued to be the root cause of CS by many [1,19,105–108]. While she Sensory Conflict/Mismatch Theory is not without critics [34,109], it is still a widely known and studied phenomenon in causing CS and was therefore added as a possible cause of CS.

The Postural Instability Theory was originally proposed by Riccio and Stoffregen and argues that CS is an effect of instability in the posture of the user. The theory provides three requirements that must be met for CS to occur, namely that postural instability must be present, the user's posture must precede the CS and individual differences should indicate who is most likely to experience CS [34]. Riccio and Stoffregen [34] found that an increase in postural sway, for example, the velocity, range and variance, increases the onset of CS. However this theory has been criticised for various reasons, most notably, due to the lack of standard methods to measure and compare CS between users [11,12,34,110]. Regardless of the criticism, the Postural Instability Theory is still a commonly referred to phenomenon that causes CS [111] and was, therefore, included as a possible CS cause in the CyPVICS Framework.

The Vertical Mismatch Theory was proposed by Bos et al. [36] and sought to further advance the original Sensory Conflict/Mismatch Theory. They argued that the effect of CS may be caused by watching various displays. The theory suggests that all types of motion sickness (including CS), manifest in a difference in sensed verticality from the user's eyes vs the actual verticality, as experienced by the user [14,53]. Even though the theory is not as widely known, it has been referred to more often and it has links to the Sensory Conflict/Mismatch Theory and was, therefore, added as a possible cause of CS.

4.2.1.1. Momentum-associated causes: prevention or minimisation methods and techniques. On the CyPVICS Framework (Fig. 4), the possible methods to reduce CS based on the momentum-associated causes were identified as improved models of interaction,

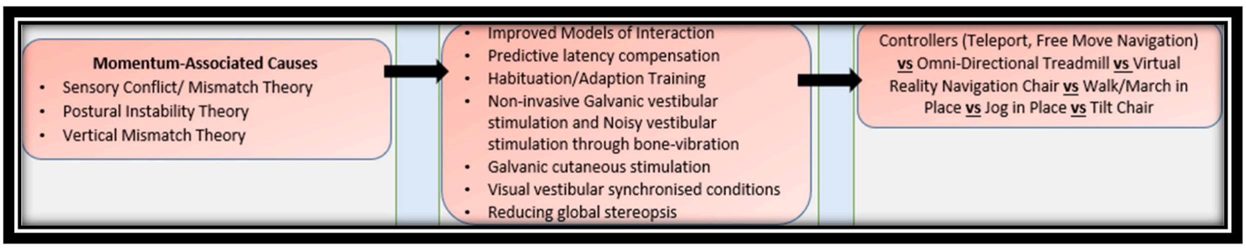

Fig. 5. Current section of the CyPVICS Framework being discussed (Momentum-Associated Causes) **(Colour Print)**.

predictive latency compensation, habituation/adaption training, non-invasive galvanic vestibular stimulation, Galvanic cutaneous stimulation, visual vestibular synchronised conditions, and reduction of global stereopsis. These methods and associated techniques of reduction will each be discussed in the section below.

4.2.2. Improved models of interaction

The first method linked to the CS causes in this section, is that of improving the interaction models. It refers to the conceptual model that participants will expect when using the technology [112]. In the case of the CyPVICS Framework, the techniques listed are those which a participant uses to interact with a VCS or virtual objects. The various techniques were added as competitors to one another in the framework, as each technique has its own benefits and applicable field of application. Depending on the participant's required actions in the VE, a certain technique of interacting with the VCS might be the only viable solution. For example, when the participant is expected to walk physically, one would rather use the ODT than the virtual reality navigation chair (VRNChair) or the controllers.

Multiple techniques to interact with a VCS can be selected to navigate a VE. The most used and common techniques are controller based, like those found on a PlayStation or Xbox. Within the controller-based techniques, there are different ways with which the participant can navigate the VCS, using either teleportation or joysticks (free move navigation). Other VCS interacting techniques that have been used are ODTs [113], walk in place (WIP) [59], jog in place (JIP) [85], the Virtual Reality Navigation Chair (VRNChair) [82], or the tilt chair [83].

When comparing controller-based navigation techniques with, for example, WIP, each technique has its own advantages and disadvantages. In previous studies, the controller-based techniques (teleportation and joystick) had the lowest CS scores when compared to WIP. However, the difference between the two were not statistically significant [59]. While WIP or jog in place (JIP) was not proven to reduce CS [85] it is still seen as a new model of interaction and was, therefore, included as a technique for interacting with a VCS in the CyPVICS Framework. The VRNChair uses a manual wheelchair with various sensors and software which translates the movements of the chair into machine readable code for navigating immersive VEs [82]. The ODT allows the participants who are immersed in the VE using an HMD, to physically walk on the pad. This, in turn, simulates movement in the VE [113]. Aldaba and Moussavi [83] compared various techniques of interacting within VCS, namely the TiltChair, ODT, VRNChair and a controller (joystick). The results indicated that the VRNChair had the lowest CS scores and is, therefore, the most feasible to reduce CS. The VRNChair was still included in the CyPVICS Framework, as it is a valid technique for interacting with a VCS. However, as previously mentioned, the techniques of interacting with VCS will depend on the type of VCS and how the participants must be able to interact with it and its objects.

4.2.3. Predictive latency compensation

Predictive latency compensation works by predicting future head positions using head tracking information and algorithms [41]. It proved to significantly reduced the effect of CS on the participants and was a possible solution to CS [114] and was, therefore, included as a method to prevent or minimise CS in the CyPVICS Framework.

4.2.3.1. Habituation/adaption training. Habituation/adaption training refers to the repeated exposure of a participant to VR to reduce CS symptoms. For example, the participant is asked to perform tasks at different time intervals with breaks in between, while being immersed in the VE. Research showed that habituation/adaption training is an effective way to decrease CS in immersive VR participants, as participants that were repeatedly exposed to immersive VR showed significantly less CS symptoms than those that were exposed only once [63–65,67]. Therefore, habituation/adaption training was included as a method to prevent or minimise CS in the CyPVICS Framework.

4.2.4. Non-invasive galvanic vestibular stimulation (GVS)

Non-invasive Galvanic Vestibular Stimulation (GVS) refers to the stimulation of the vestibular organs (inner ear and ear canal) through vibration and it proved to be more effective in participants that experienced intense nausea during immersive VR navigation [44]. As non-invasive GVS did reduce the symptoms of CS while navigating immersive VCS [75]. Another form of non-invasive GVS is noisy Vestibular Stimulation, also referred to as noisy Galvanic Vestibular Stimulation (nGVS) [115], was also added as it proved to reduce CS when applying nGVS, through bone-vibration [73].

4.2.4.1. Galvanic cutaneous stimulation (GCS). CGS involves the use of electrodes or other cutaneous (skin) contact methods to stimulate the nerves. It has been found to be an effective way of reducing CS in immersive VR [80] and was therefore added to the CyPVICS as part of methods of prevention or minimisation and linked to momentum associated causes as it involves stimulation of the nerves as part of the sensory conflict theory.

4.2.5. Visual vestibular synchronised conditions

Visual vestibular synchronised conditions entail that the participants are positioned synchronously with what they are doing in the VE. For example, when they lean towards the left, the device (for example a chair), will also lean towards the left. This is also known as a motion coupled system and it reduced the onset of CS [45]; therefore, it was included as part of the CyPVICS Framework.

4.2.6. Reducing global stereopsis

Global stereopsis is known as the perception of depth by a participant and can be stimulated by objects that possess horizontal discrepancies. For example, a chair in the VE is in front of the table, and the user is clearly able to distinguish the depth relative to the chair. Reducing global stereopsis successfully reduced CS in the users. However, it has a negative impact on the participant's control within the VE [76]. Nonetheless it was added as a method of preventing or minimising CS, since it can contribute to minimising CS during VCS.

The following section describes the development and usability causes, along with their associated CS prevention or minimisation methods and techniques.

4.2.7. Development and usability causes

The next group of causes was classified as 'Development and Usability Causes' and included severe framerate fluctuations, low VE/system usability, varying latency, rotational movements, and acceleration (Fig. 6). They share two common methods to prevent or minimise CS, namely usability and UX, and software/system design.

The first cause in this category is that of severe framerate fluctuations and display lag [53]. Framerates are determined in frames per second (fps) and dictate the rate at which a screen will display a new image to make it look like a continuous stream. A normal screen will run at 60Hz or 60fps, which means that the screen shows 60 images every second. However, in some cases the load on the device might be too much to handle, or an error might occur, and the framerate might drop to 30fps, and then go back to 60fps [116]. These severe framerate fluctuations could induce CS [54]. Framerate fluctuations along with hardware and other software issues can lead to display lag, which also induces CS [53].

Low VE/system usability simply refers to a VE or system that does not provide a satisfying UX, or is deemed difficult to use or navigate [117,118].

Varying latency is the process that occurs when a participant tries to perform an action in the VE, for example, reaching for the ball, and a few milliseconds later the avatar (the virtual representation of the participant) in the VE reacts and picks up the ball. Normally, the latency is so low that the human eye cannot pick it up. However, if the latency starts varying a lot, for example, rapidly goes from fast to slow, or vice versa, it can induce CS [119].

Rotational movements refers to rotations that the participant must perform with, for example, the joystick of the controller, while remaining in a stationary position. Too much rotational movement required of the participant in a VCS can also lead to increased CS [19,47].

Acceleration is the momentum of the users avatar within the VE, for example, when a user plays a race car game the acceleration varies according to the user's choice of speed that the race car must travel. Acceleration was found to be a cause of CS, since sudden acceleration can increase CS in immersive VR users [47].

4.2.7.1. Development and usability causes: prevention or minimisation methods and techniques. The above-mentioned causes all share the same possible methods to prevent or minimise CS, namely usability and user experience (UX) and software/system design methods.

4.2.7.2. Usability and user experience (UX). Usability and UX are often confused and seen as the same construct. They are, however, separate terms, although both are used to measure the interaction of humans with technology. Usability and UX require a participant to perform tasks specific to the technology in question [118,120]. Both constructs provide developers and researchers the opportunity to test a system (prevention or minimising technique), in this case, a VE for immersive VR. By conducting such tests, the developers can fix issues with the VE that might eventually induce CS; therefore, usability and UX were included in the CyPVICS Framework. The CRUX Model [30], along with other research [59,87], indicated that a VE with a good usability level and a good UX could assist in reducing CS symptoms. The CRUX model shows the links between aspects that affect user experience (UX) and aspects that affect creativity [30]. From the CRUX Model, the aspect of UX was taken as a possible method to reduce CS.

4.2.7.3. Software/system design. The software/system design method was added as an overall header in the CyPVICS Framework to encapsulate all the methods that need to be addressed by a developer during the creation, redevelopment, or updating of the VE. The techniques that can be implemented by a developer to reduce CS include the current best design practices by the various VR development platforms [87], rotation blurring [91], field of view restriction/control [42,88], reversed visual flow direction [90], spatial

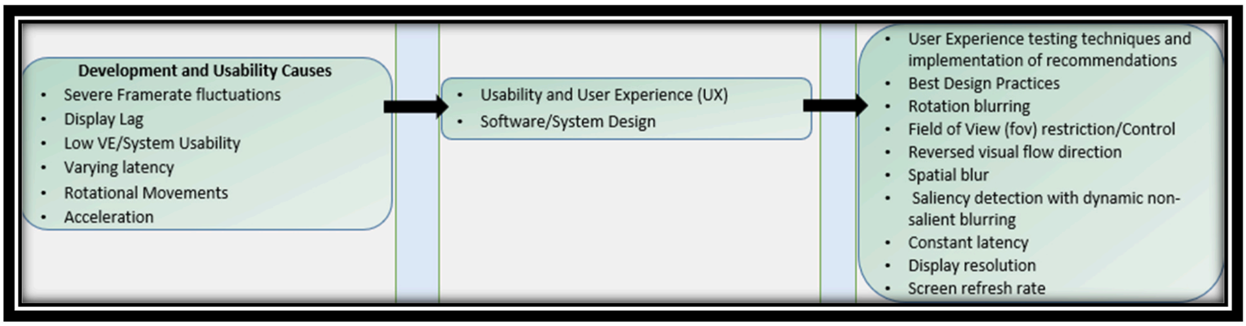

Fig. 6. Current section of the CyPVICS Framework being discussed (Development and Usability Causes) **(Colour Print)**.

blur [98], saliency detection with non-salient blurring [96], constant latency [119], recommended screen resolutions [60] and recommended screen refresh rates [61].

Each of the CS minimisation or prevention techniques associated with the usability and UX, and software/system design methods, will be discussed in the sections to follow.

4.2.8. Best design practices

The best design practices were included as a CS reduction technique in the CyPVICS Framework. Certain best design practices need to be followed when creating/developing an immersive VE, as they can contribute to minimising or preventing CS. Before creating a VE, the software engineer should familiarise himself with current best design practices in the field of VE development. These include current software design principles and VE development best practices [87], available from development platforms, such as Unity [121] or Unreal Engine [122]. Some of the best design practices were emphasised in literature as the most common software design issues, and were, therefore, included as separate headings, such as rotation blurring and constant latency, which is discussed later.

4.2.9. Rotation blurring

Rotation blurring refers to the action of consistently blurring the entire screen while the participant rotates. Research has indicated that rotation blurring can significantly reduce CS, while also delaying its onset and was, therefore, included as part of the CyPVICS Framework. Participants who experienced acute high levels CS tend to benefit the most from rotation blurring [91].

4.2.9.1. Field of view restriction/control. To restrict or control a participant's field of view in immersive VR implies limiting what the participant can see. To explain: a normal field of view of 96° can be limited to 60° to reduce CS. Various research studies have shown that by restricting the field of view or dynamically controlling the field of view, a significant drop in CS symptoms occurs [42,62,88,89,92–95,99]. Therefore, field of view restriction/control was added as a technique to minimise or prevent CS in the CyPVICS Framework.

4.2.9.1. Reversed visual flow direction. Reversing the visual flow direction was determined to be a valid technique to reduce CS. However, it requires the participant to move "backwards" in the VE [90], which is not a viable solution in most VE use cases. It can, nonetheless, reduce CS symptoms in immersive VR participants and was, therefore, added to the CyPVICS Framework.

4.2.10. Spatial blur

Spatial blur refers to the action of blurring the image or VE background to match the participant's spatial presence. For example, objects that are far away are more blurred than objects that are close by. Spatial blur is used to match the focus within the VE with that which the participant would experience in the real world. Applying spatial blur proved to significantly reduce CS symptoms [62,98], and was, therefore, added as a technique to minimise or prevent CS in the CyPVICS Framework.

4.2.11. Saliency detection with non-salient blurring

Saliency detection seeks to find salient (noticeable) objects within a computer-generated image or VE before the image is processed for display. On the other hand, non-salient blurring seeks to dynamically blur objects that are not salient (unnoticeable). It provides the participant with a salient point or object to focus on, while the rest of the non-salient objects are blurred. By identifying objects that are salient in the VE and then blurring non-salient objects, researchers have found that CS was significantly reduced during VE navigation [96,97,123] and was, therefore, added to the CyPVICS Framework.

4.2.11.1. Constant latency. Latency, also referred to as delay, is when there is a delay between the physical participant action and the action that the avatar performs in the VE, for example, when the participant moves his/her head, but the display does not react immediately, only milliseconds later [124]. Latency can negatively influence immersive VR participants and by keeping the latency within the VE at a constant rate with as little delay as possible the onset of CS during immersive VR navigation is decreased [119]. This is why constant latency was included as a technique in the CyPVICS Framework.

4.2.12. Display resolution

Display resolution refers to the number of pixels per inch that a digital screen can display, examples of common resolutions include 1080P (high definition) and 4K (ultra-high definition). Lim et all [60] determined that lower resolutions can lead to higher levels of CS, and seeing how resolution is linked to hardware and design specifications, it was incorporated into the software/system design as an associated minimisation or prevention technique.

4.2.12.1. Screen refresh rate. Wang et al. [61] determined that refresh rates of the screen in a HMD has an effect on CS onset. Their research indicated that using a refresh rate lower than 120 induces higher levels of CS and recommend that a minimum of 120Hz refresh rate be implemented in HMDs. Seeing that this is a hardware and development issue, it was added to system/software design.

In the following section, increased workload, as a CS cause on the CyPVICS Framework, will be discussed.

4.2.13. Increased workload

Increased workload, as a cause of CS in the CyPVICS Framework, implies a heavy or increased workload while being immersed in a VE. The proposed solution (method) to this CS cause, is to decrease the workload (Fig. 7). The workload refers to what the participant has to do in the VE, for example, monitoring the patient while administering drugs and monitoring the vitals [31]. A good practice would be to reduce the overall workload in the VE to exclude or limit the possibility of workload causing a participant to experience CS [62]. The human brain, although very powerful, is not wired to handle multiple tasks at once [125–127]. The solution to this will be to limit the workload on the user's cognitive function to three or four tasks or items at a time when possible and it was subsequently added to the CyPVICS Framework.

The following section describes the Rest Frame Theory along with its associated CS prevention/minimisation method.

4.2.14. Rest frame theory

The Rest Frame Theory (Fig. 8) argues that CS is caused by a mismatch in the actual gravity and direction, and the sensed gravitation and up direction in the VE. This can cause a participant to become unbalanced. The theory argues that by providing a rest frame (a static or dynamic object or line which is relative to the real world, for example, a virtual nose [56] or a motion singularity point to focus on during navigation [58]) to give the participant a sense of direction while immersed in a VE, would decrease CS. While there are contradicting cases where a rest frame did not reduce the effects of CS [1,12,128], it was still added to the CyPVICS Framework as it could be a possible cause with a possible solution for some users [1,12,49,57,62,128].

Causes of CS that have no known associated methods or techniques, will be discussed in the section to follow.

4.3. Causes of CS not added to CyPVICS

During the creation of the CyPVICS Framework, a few CS causes, with no associated prevention or minimisation methods or techniques, were identified from literature. These causes were the Poison Theory, Insomnia, and ocular refraction disorder. The justification for not adding these causes can be found under each of their respective headings.

4.3.1. Insomnia

Insomnia is a common sleep disorder that makes it difficult for someone to fall sleep or stay asleep, and has been known to be a possible cause of CS [52]. While insomnia proved to be a viable cause, the intervention requires medication and in the case of the CyPVICS framework the authors cannot condone the use of drugs as a method to limit CS as this requires the intervention of a medical professional.

4.3.2. Poison theory

The Poison Theory refers to the participant's instinctual reaction to dangerous toxins. In the case of CS, it constitutes the unnatural feeling while navigating the VE [33]. The Poison Theory is widely criticised, as it is unpredictable and not all participants experience it. Also, the evolutionary reaction referred to in this theory is vomiting, which does not happen to all participants [33,109,129]. Due to the lack of evidence in recent literature of this theory and the wide criticism it was excluded from the CyPVICS framework.

4.3.3. Ocular refraction disorder

Ocular refraction disorder refers to vision problems that make it hard to see clearly, for example, near-sightedness (myopia), farsightedness (hyperopia), astigmatism and presbyopia [130]. While it is proven that users suffering from an ocular refraction disorder are more susceptible to CS [60], it was not added, due to the fact that it requires the intervention of a medical professional.

In the section to follow, possible CS reduction methods will be discussed which were not linked to a specific cause.

4.4. Methods and techniques of preventing or minimising CS without causes

Various CS detection methods and techniques were identified from literature which could not be linked to a specific cause. These methods were classified under the heading 'Methods of Preventing or Minimising CS without Causes' in the CyPVICS Framework (Fig. 9).

The only method included was that of early CS detection. Even though the detection of CS is not necessarily a method to prevent or minimise CS, *early* detection can assist to detect CS before it manifests. One can then either apply the appropriate prevention or minimisation techniques, or the participant can be stopped during their VE navigation to prevent the manifestation of CS. In doing so, the participants are spared the discomfort of experiencing CS, which justified its inclusion in the CyPVICS Framework for this study.

4.4.1. CyberSense framework

CyberSense is a closed-loop framework that collects participant data while participants are immersed in a VE. The CyberSense framework detects when the participant is near to experiencing CS, and then uses an engine that applies known CS reduction techniques, such as field of view restriction, dynamic blurring, or rotation blur. CyberSense then returns to detecting CS and applying reduction techniques as it deems necessary in an attempt to reduce the participants' CS levels [26] CyberSence provides a

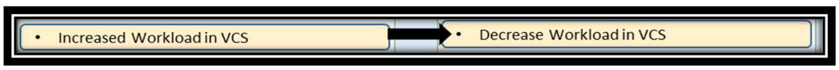

Fig. 7. Current section of the CyPVICS Framework being discussed (increased Workload) **(Colour Print)**.

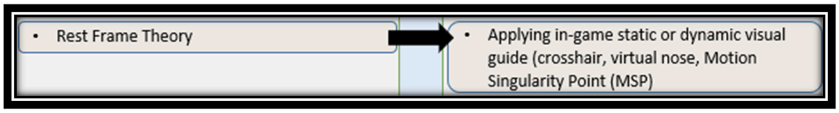

Fig. 8. Current section of the CyPVICS Framework being discussed (Rest Frame Theory) **(Colour Print)**.

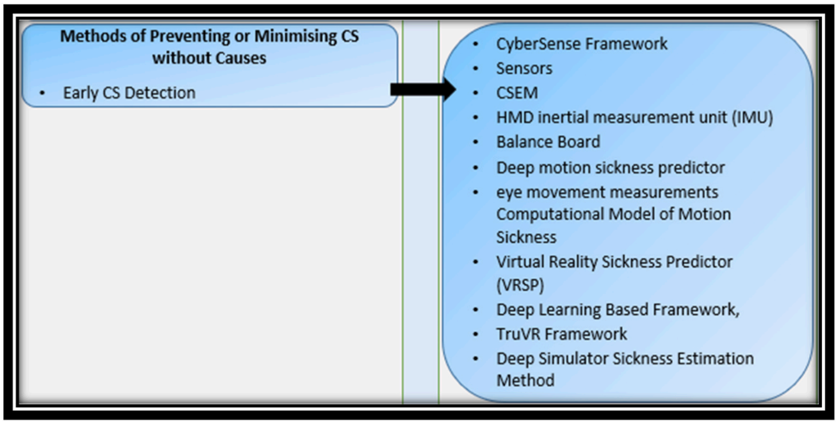

Fig. 9. Current section of the CyPVICS Framework being discussed (Methods of Preventing or Minimising CS without causes) **(Colour Print)**.

non-disruptive means to manage the onset of CS during user navigation in immersive VR and, therefore, was included as a CS detection and reduction method and was therefore included in the CyPVICS Framework.

4.4.2. Sensors

Sensors refer to technology that a participant can wear while navigating a VE. The sensors assist in detecting the onset of CS, for example, when wearing a brain-computer interface (BCI) [25] or using electrodermal activity (EDA) [50], cardiac activities [102] or HMD integrated sensors such as eye tracking, head tracking and motion [103]. Sensors are often used in conjunction with other sensors, or with some sort of software, for example, the CyberSense framework [26]. Although it can be used in conjunction with other techniques, it was added as a separate technique to the CyPVICS Framework, since it can be used on its own as well.

4.4.3. Cybersickness estimation model (CSEM)

The CSEM is a physiological model that uses software along with an array of various sensors to predict the onset of CS during immersive VR navigation. The CSEM accurately predicted the onset of CS in the past and can be used to provide an objective measure to determine whether a participant is starting to experience CS symptoms, or not [27]. The entire CSEM was added to the CyPVICS Framework as a possible method for detecting CS during immersive VR navigation.

4.4.4. HMD inertial measurement unit (IMU)

Kim et al. [42] validated a new technique for determining CS, which used the built-in inertial measurement unit (IMU) of a mobile HMD. The IMU is a sensor that is built into electronics that measure force, angles, and orientation. By using the built-in IMU, it is possible to obtain head sway data to assist in determining the level of CS. Even though the IMU is technically seen as a sensor, it was separately specified in the CyPVICS Framework, as the research that gave way to its inclusion was IMU-specific and did not include any other sensors.

4.4.5. Balance board

The balance board or Wii balance board is a piece of equipment that tracks a participant's centre of balance to keep him/her level. Dennison and D'Zmura [51] determined the effect of unexpected visual motion on postural sway and CS. Their research measured postural instability, by means of a Wii balance board on which the participants had to stand to determine the effect or onset of CS in the participants. The balance board accurately predicted postural instability. However, they did specify that unexpected visual alarms did not lead to increased CS [51]. The balance board was, however, still included in the CyPVICS Framework, as there was potential in its ability to detect CS.

4.4.6. Deep motion sickness predictor

Jinwoo et al. [100] set out to create a new technique to predict CS. They did this by creating a network that imitated and learned the neurological mechanisms of CS and expressing the spatial and temporal domains over the generated frame. Once all stages were completed, their model was able to calculate the possibility of CS onset per frame. Their results indicated that the deep motion sickness predictor had excellent performance, and could be used to determine the onset of CS. Therefore, it was included in the CyPVICS Framework.

4.4.7. *Eye movement measurements*

Chang et al. [14] investigated the Subjective Vertical Mismatch (SVM) Theory as a possible cause of CS. With their study they sought to prove the SVM Theory by measuring the participant's eye movement and to determine whether the subjective level of CS could be predicted using eye movement measurements. Their research concluded that eye movements could potentially indicate the onset of CS during immersive VR navigation. While no definitive link could be established between the SVM and eye movement, eye movement measurements were included in the CyPVICS Framework, since it did succeed in predicting the onset of CS.

4.4.8. *Computational Model of Motion Sickness*

The Computational Model of Motion Sickness seeks to predict CS based on the motion stimulus the participant receives. This model uses the predictability of motion patterns to determine whether CS will manifest. The model was tested by means of experimentation and even though no significant differences were found between this model and its predecessors [29], the newest version was included in the CyPVICS Framework, as it is an accepted model in the field of CS research.

4.4.9. *Virtual Reality Sickness Predictor (VRSP)*

The VRSP was added as a possible method to detect CS since it proved to be an effective way of determining the onset of CS, it was subsequently added a possible early CS detection method. The VRSP was trained by feeding in subjective participant data and can subsequently be used to determine the onset of CS with an accuracy of 72 % [37].

4.4.10. *Deep Learning Based Framework*

The Deep learning Based Framework uses deep neural networks in an effort to predict the onset of CS and to determine the severity thereof [38]. While in the early stages of development, it was still added as a potential early CS detection method as it did show positive results.

4.4.11. *TruVR framework*

TruVR uses explainable machine learning (xML) to detect and minimise CS. TruVR predicted CS with an accuracy of more than 94 % in two separate datasets [39]. The TruVR Framework was therefore added as a potential method to accurately detect the onset of CS in VR.

4.4.12. *Deep simulator sickness estimation model*

Zhau et al. [104] presented a method to detect CS, by incorporating a deep neural network that collected data from the users while they were immersed in the VE. Their study proved that their method was reliable in predicting the onset of CS and was therefore included as an early CS detection method under the associated minimisation or prevention techniques.

In the following section various methods of preventing or minimising CS, which could not be linked to a cause or techniques in the CyPVICS Framework will be discussed.

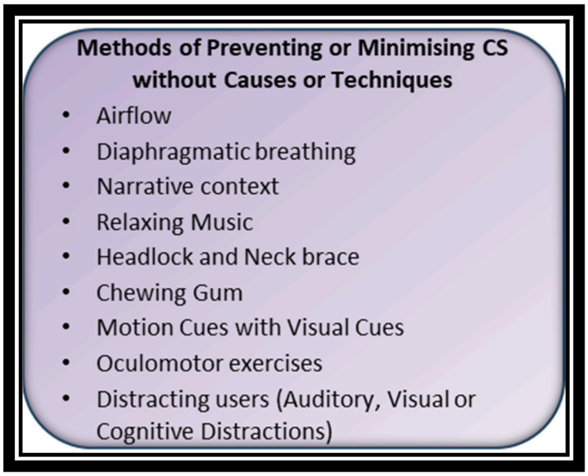

Fig. 10. Current section of the CyPVICS Framework being discussed (Methods of Preventing or Minimising CS without Causes or Techniques) **(Colour Print)**.

4.5. Methods of preventing or minimising CS without causes or techniques

CS reduction methods also exist that could not be linked to a specific cause, or technique, for minimising or preventing CS. These unlinked CS minimisation or prevention methods could reduce CS, regardless of the cause, and were classified in the CyPVICS Framework under the heading 'Methods of Preventing or Minimising CS without Causes or Techniques' (Fig. 10).

These methods include airflow, diaphragmatic breathing, narrative context, relaxing music and headlock and neck brace, and each of them will be discussed in the sections to follow.

4.5.1. Airflow

D'Amour et al. [71] determined the effect of airflow (continuous air, like a fan or wind, blowing on the participant) and seat vibration on CS. The results from the study indicated that airflow significantly reduced the effects of CS, while seat vibration did not. This was validated in a later study on immersive bicycle VR [72]. Airflow was included in the CyPVICS Framework for this study, as it did reduce CS, while seat vibration was excluded, as it did not have an impact on CS.

4.5.2. Diaphragmatic breathing

Diaphragmatic breathing is known as deep, controlled, and regular breathing at around three to seven respirations per minute. Research has shown that diaphragmatic breathing is a valid way to significantly reduce CS symptoms in immersive VR participants, thus being included in the framework [68,69].

4.5.3. Narrative context

The narrative context refers to the context in which a story is told or viewed. For example, it might be difficult for someone to understand the story if they did not understand the context in which the story takes place [131]. Kenny et al. [74] determined that presence and CS were negatively correlated, while the narrative context increased presence. Their results proposed that both CS and presence could be modulated in such a way that the participant can experience high presence with low CS when pursuing a top-down intervention like narrative context. Therefore, narrative context was included in the CyPVICS Framework.

4.5.4. Relaxing music

Keshavarz and Hecht [70] tested whether different types of music might reduce CS. The research used various groups which listened to different types of music (relaxing music, neutral music and stressful music). The results indicated that the relaxing music decreased the severity of CS, while stressful or neutral music did not. Hence relaxing music was added as a reduction method in the CyPVICS Framework.

4.5.5. Headlock and neck brace

Headlock, in the context of this study, is known as a method where the participant keeps one eye closed. This freezes the image until the participant has moved his/her head and opened the eye again. Various research studies have shown that by implementing headlock in both immersive and non-immersive VR settings, CS could significantly be reduced, and even more so when a neck brace is added into the mix [19,83]. Seeing that it reduced CS, both were added to the CyPVICS Framework.

4.5.6. Chewing gum

Kaufeld, De Coninck, Schmidt and Hecht [132] determined that chewing gum while immersed in a VE leads to a significant reduction in CS onset while also proving a cheap and easy to administer countermeasure to limit CS symptoms and it was therefore included in the CyPVICS Framework.

4.5.7. Motion cues with visual cues

Motion cues are mechanisms by which a user can sense the motion of their body in relation to the physical environment while visual cues highlight important aspects or information. One study determined the advantage of using motion and visual cues in combination to reduce CS and found that CS decreases significantly when using both motion and visual cues while a user is immersed in a VE [78]; it was subsequently added to the CyPVICS Framework.

4.5.8. Oculomotor exercises

Kim et al. [79] determined that CS could be reduced by exposing the user to various oculomotor exercises, such as horizontal head movement, saccadic eye movement exercises and perusing a target with the eyes while keeping the head stationary. Oculomotor exercises was included in CyPVICS seeing that it could be used in any case of CS regardless of the cause.

4.5.9. Distracting users (auditory, visual or cognitive distractions)

One study reported on the use of various distraction methods to limit the onset of CS. The study found that using auditory, visual and cognitive distractions all proved useful in limiting the onset of CS in participant [81]. The use of distractions was therefore added as a general way to limit or prevent CS in the CyPVICS Framework.

5. Conclusion

For this study, a novel contribution, namely the CyPVICS Framework for reducing or eliminating CS during VCS, was forged from existing literature. The CyPVICS Framework consists of various elements that were sourced from and supported in literature, applying the best fit framework [5]. The framework illustrates the link between presence, realism, and CS by indicating that realism increases presence in immersive VCS, but presence also increases CS − when CS occurs it decreases the user's presence. From the literature, various causes of CS, along with linked methods and their associated techniques for reducing or minimising CS, were identified and included in the flow of the CyPVICS Framework.

The CyPVICS Framework encompasses the volatile and mind-bending nature of CS in that it demonstrates that even though one solution could reduce CS, another CS cause could present itself. As an example, the user might be fine while being exposed to non-invasive galvanic vestibular stimulation, only for an extreme latency spike to occur which induces CS. The CyPVICS Framework also emphasises the importance of good software design practices and the use of Usability and UX testing to improve VEs and equipment to assist in reducing CS while immersed in a VE. This framework has the potential to be used in fields other than immersive VCS, because, as mentioned, the roots of the CyPVICS framework were built on CS in general and not only on the base of clinical simulation for health professionals. Ultimately the CyPVICS Framework can provide future researchers with a theoretical starting basis for CS research while also providing developers of immersive VR software with practical insights into causes of CS and how they can go about dealing with the issue of CS.

As with most research, it is not without its limitations. The CyPVICS framework is dynamic and can change based on new evidence, while the CS causes and reduction methods and techniques which could not be linked, need to be investigated further to determine their validity. Furthermore, the strength of the relationships between the various causes and methods of prevention or minimisation can be explored in future research.

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Ethical clearance

This study was reviewed and approved by GENERAL/HUMAN RESEARCH ETHICS COMMITTEE (GHREC) of the University of the Free state, with the approval number: UFS-HSD2021/1126/21.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Benjamin Stephanus Botha: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lizette De wet:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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