Virtual Reality
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ORIGINAL ARTICLE

A meta-analysis of the virtual reality problem: Unequal effects of virtual reality sickness across individual differences

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Abstract

Practical applications of virtual reality (VR), defined as a three-dimensional digital representation of a real or imagined space, have become increasingly popular and are now applied in workplace training, physical rehabilitation, psychological therapy, and many other settings. Feelings akin to motion sickness, called VR sickness, can arise from interacting with VR programs, and researchers have shown that certain aspects of the user, such as gender and age, may predict the occurrence of VR sickness. The unequal effects of VR sickness are a dire concern and the application of VR is unfair to certain users if they are prone to sickness. For instance, a workplace VR training program could result in disparate treatment if women experience more VR sickness than men. To investigate this notion, we perform a meta-analysis on the relationship between VR sickness and a wide array of potential antecedents. The results demonstrate that motion sickness susceptibility, gender, real-world experience, technological experience, possessing a neurological disorder, and possessing a relevant phobia all significantly relate to VR sickness; however, no moderating effects produced recurrent significant results. These results were partially explained by the current dominant framework for VR sickness, postural instability theory, but some findings were not predicted by the theory. Therefore, we support that (a) VR sickness produces unequal effects across multiple individual differences; (b) these effects appear resilient across applications of VR programs, and (c) further research is needed to develop theory and identify explanatory mechanisms that detail these relationships.

Keywords Virtual reality · Cybersickness · Virtual reality sickness · Virtual reality-induced symptoms and effects · Individual differences · User attributes · Head-mounted displays

Since the rise of low-cost immersive hardware (e.g., head-mounted displays[HMDs]), practical applications of virtual reality (VR)[1] have become increasingly popular and are now applied in workplace training (Grabowski and Jankowski 2015; Howard and Marshall 2019), physical rehabilitation (Ravi et al. 2017; Tieri et al. 2018), psychological therapy (Carl et al. 2019; Morina et al. 2015), and many other settings (Didehbani et al. 2016; Howard 2019; Ip et al. 2018; Lorenzo et al. 2016; Sherman and Craig 2018; Valmaggia et al. 2016). VR can be used as a cost-saving measure if the medium can eliminate the need for human interaction, and researchers have even shown that VR interventions often produce more desirable outcomes than comparable alternatives (Carl et al. 2019; Howard 2019). Across these studies, researchers have also discovered a powerful detriment to VR intervention efficacy: VR sickness.

VR sickness refers to feelings akin to motion sickness that arise during VR experiences (e.g., nausea, vomiting, vertigo), and it is also called simulator sickness, VR-induced symptoms and effects (VRISE), as well as a host of other terms (Cobb et al. 1999; Kennedy et al. 1992a, b; Kim et al. 2018). While no one theory is currently dominant to explain VR sickness, postural instability theory (PIT) is among the most supported (Dennison and D'Zmura 2017; Koslucher et al. 2016; Li et al. 2018; Lim et al. 2018; Stoffregen et al.

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[1] We consider VR to be any three-dimensional digital representation of a space, including both VR presented via non-immersive and immersive hardware. Some consider only VR presented via immersive hardware to be "true VR" and VR presented by non-immersive hardware to be "VR 2.5D", but we use this broader interpretation due to its prevalence and the study of moderators allows us to provide separate results for VR, "true VR", and "VR 2.5D".

2000). PIT suggests that VR sickness arises from sensory disparities in the visual and vestibular systems that cause poor balance and uncontrollable postural movements, and an evolutionary advantage of humans is to purge after experiencing such postural effects due to possible deadly causes (e.g., ingesting poison). Factors that cause greater postural instability and/or elevate perceived disparities between the visual and vestibular systems are believed to be antecedents of VR sickness.

Using this theory and similar others, several aspects of VR programs have been identified to influence VR sickness, such as immersive hardware or software latency (Chessa et al. 2019; Howarth and Costello 1997; Kemeny et al. 2017; Kennedy et al. 2010; Sharples et al. 2008). A separate stream of research has supported that aspects of the user may also predict VR sickness, including gender and age (Munafo et al. 2017; Kim et al. 2018; Tyrrell et al. 2018; Zhang et al. 2016). In general, these studies have suggested two possibilities for these antecedent effects. First, certain individual differences may cause individuals to have more or less control over their postural stability (e.g., age, physical disabilities), and, when interacting with VR, these individuals experience smaller or greater postural instability and subsequently VR sickness. Second, other individual differences may cause individuals to be more or less sensitive to disparities in their visual and vestibular systems (e.g., prior experience, visual acumen), and these individuals perceive greater or smaller disparities that cause postural instability and therefore VR sickness.

The unequal effects of VR sickness on users are a dire concern and the application of VR is unfair to certain users if they are prone to sickness. For instance, a workplace VR training program could result in disparate treatment if women experience more VR sickness than men (and thereby suffer reduced outcomes; Krieger 2004; Landau 1995). To investigate this notion, we perform a meta-analysis on the relationship between VR sickness and a wide array of individual differences that may relate to either greater postural instability or greater perceived visual/vestibular disparities. The current results therefore determine the extent that these individual differences predict VR sickness, but they also test whether an antecedent category (postural instability or disparities) produces more reliable effects as well as the overall validity of PIT in explaining VR sickness. The studied antecedents include motion sickness susceptibility (both), gender, age, well-restedness, possessing a neurological disorder (postural instability), relevant real-world experience, technological experience, immersive tendencies, visual acumen (disparities), possessing a psychological disorder, possessing a phobia, and cognitive abilities (neither) (Table 1). We test for moderating influences on these relationships, including the display hardware, input hardware, type of software, participant population, source type, and publication year. These moderation tests can determine whether the relationships of VR sickness and various individual differences are robust across practical applications of VR, as they can be considered robust if these moderators do not influence the magnitude or direction of results.

The current article poses both practical and theoretical considerations. Practically, our results can suggest whether real-world applications of VR should be closely monitored until VR sickness is no longer a concern with modern hardware and software, as many practitioners would face legal ramifications for applying technologies biased against certain populations (e.g., women, elderly). Theoretically, we apply PIT to hypothesize relationships between various individual differences and VR sickness, and our meta-analytic results can therefore assess the ability of PIT to predict and explain such relationships. While the theory can explain many dynamics of VR sickness, it is possible that PIT is unable to elucidate the effects of individual differences. Lastly, the relation of individual differences and VR sickness has been recognized for decades (Cobb et al. 1999; Kennedy et al. 1992a, b), but few authors have integrated and summarized prior findings. By providing perhaps the first quantitative synthesis, we unify extant research to identify current knowns and unknowns regarding VR sickness. We distinguish relations that are robustly supported and necessitate less future research as well as those that have been sparsely investigated and demand additional investigations. Thus, we identify a directed course of investigation for future research to better understand VR sickness.

Before continuing, however, we differentiate our work from prior systematic literature reviews and meta-analyses of VR sickness. Davis et al. (2014) conducted systematic search procedures in conducting their review for all aspects of VR sickness, but they did not provide quantitative inferences. The current article not only provides quantitative results regarding our meta-analytic findings, but we also provide numerical information regarding the frequency of certain aspects of study design in investigations of VR sickness (e.g., use of hardware, studied populations). Chang et al. (2020) performed a systematic literature review of all predictors of VR sickness, and they conducted a meta-analysis to assess whether fidelity predicts VR sickness. Their review only partially discussed individual differences, and their meta-analysis did not study individual differences. The present review provides more in-depth insights into the role of individual differences in VR sickness, and our meta-analysis provides wholly unique information from this prior article. Saredakis et al. (2020) performed a systematic literature review of many aspects that may influence VR sickness, but they largely focused on hardware and software. Their meta-analysis did include age and sex, but they analyzed these variables by conducting analyses based on the average age and proportion of females in their included samples. The current article studies these and other individual

Table 1 Studied variables and association with VR sickness

Variable	Proposed relationship with VR sickness	Postural instability or disparity hypothesis?	Summary of proposed relationship
(1) Motion sickness susceptibility	Positive relationship	Both	May either experience greater postural instability or perceive greater visual/vestibular disparities
(2) Gender	Women experience more VR sickness than men	Postural Instability	Women have worse postural stability than men
(3) Age	Positive relationship	Postural instability	Older individuals have worse postural stability than younger individuals
(4) Well-Restedness	Negative Relationship	Postural Instability	Being well-rested improves resources to control postural stability
(5) Neurological disorder	Those with a neurological disorder experience more VR sickness than those without	Postural instability	Those with a neurological disorder possess worse physical capabilities to control postural stability
(6) Real-world experience	Positive relationship	Disparity	More likely to notice disparities in virtual (visual) and real-life (vestibular) activities
(7) Technological experience	Negative relationship	Disparity	More accustomed to disparities between visual and vestibular systems when interacting with technology
(8) Immersive tendencies	Negative relationship	Disparity	More easily able to perceive visual environment as own environment and disregard visual/vestibular disparities
(9) Visual acumen	Positive relationship	Disparity	More likely to observe visual disparities from vestibular system
(10) Psychological disorder	Those with a psychological disorder experience more VR sickness than those without	Neither	No previously proposed relationship with VR sickness
(11) Relevant phobia	Those with a relevant phobia experience more VR sickness than those without	Neither	No previously proposed relationship with VR sickness
(12) Cognitive abilities	Unknown	Neither	No previously proposed relationship with VR sickness

differences by conducting a meta-analysis that aggregates the reported effect sizes representing the relations of these individual differences and VR sickness, which provides a more accurate assessment of their relations than analyzing sample characteristics. Thus, the current article studies a much wider scope of individual differences using analyses that can provide more accurate inferences than prior systematic literature reviews and meta-analyses.

1 Background

1.1 Virtual reality

VR is a three-dimensional digital recreation of a real or imagined space with interactive properties, and applications of VR can greatly vary in design and content (Carl et al. 2019; Sherman and Craig 2018; Tieri et al. 2018). For instance, students can learn chemistry abilities by using a keyboard and mouse to interact with three-dimensional digital representations of microscopic spaces presented on a HMD, and physician residents can develop surgical and treatment skills by using medical tools with sensors to interact with three-dimensional digital representations of the anatomy and physiology of patients presented on a monitor. While these two examples are very different, they both represent modern applications of VR. To understand the variations of VR, it is necessary to discuss relevant hardware and software.

Most applications of VR are still presented on computer monitors, likely due to their widespread availability and low cost (Dang et al. 2018; Diemer et al. 2015; Howard 2019). While monitors are two-dimensional, they can nevertheless present a three-dimensional representation, which is evidenced by many popular computer games (e.g., Fortnite, Minecraft). Some authors differentiate VR presented on a computer monitor as 2.5D, desktop VR, and other similar labels; however, these instances are still considered VR given present definitions (Didehbani et al. 2016; Ip et al. 2018; Lorenzo et al. 2016; Steuer 1992). Alternatively, VR can also be presented via advanced display devices, such as HMDs and CAVEs, which are almost always labeled immersive hardware or immersive VR (Cruz-Neira et al. 1993; Mon-Williams et al. 1993; Sharples et al. 2008). HMDs include displays immediately in front of the user's eyes, and any part of their field of vision not covered by the display is typically enveloped by plastic or fabric to conceal the outside world. The presented visual information is typically aligned with the user's head movements, such that the user can naturally look around in the digital environment in an immersive experience. CAVEs are multiple monitors or projectors placed around the user, which are synced to present a surrounding and immersive experience. Both technologies are believed to elicit more presence than computer monitors, and users often report favorable reactions to these technologies (Howard 2017; Munafo et al. 2017).

Like hardware, VR software can also greatly vary. VR programs may present lifelike graphics, but they can also be rather simple. These programs can also be relatively open-ended, and users may explore their digital environment; however, they can also be relatively closed-ended, and users may only perform directed activities in their digital environments. To better understand the varied nature of these programs, many authors have created typologies of VR software elements that identify the aspects for which VR may be defined (Boletsis 2017; Messinger et al. 2008; Muhanna 2015; Steuer 1992). Common elements include purpose, place, and platform (with varied labels). Even yet, some authors have created more narrow typologies of certain elements, thereby identifying sub-elements of these elements. For instance, many authors have created gamification typologies to define the different manners that software can be gamified, which often include points, badges, and leaderboards (Armstrong et al. 2015; Bedwell et al. 2012; Nacke and Deterding 2017). Therefore, VR software can be defined by an almost unlimited number of elements, each of which may have sub-elements of their own.

When discussing the relationship of individual differences and VR sickness, we consider all applications of VR. That is, our predictions are tested by aggregating studies that utilize all types of VR hardware and software, and we expect these relationships to potentially emerge across all applications of VR. We do, however, test for moderating influences of hardware and software, and we assess whether the differing nature of VR may cause individual differences to predict VR sickness in certain applications and not others. In doing so, we provide results regarding the relationships of individual differences and VR sickness separated by various subsets of VR applications (e.g., non-immersive hardware alone, traditional input alone). While we provide a holistic perspective regarding the relationship of individual differences and VR sickness, we also provide specific inferences regarding these relationships in particular contexts. We propose these possible moderators after hypothesizing the overall effects below.

1.2 Postural instability theory

The study of VR sickness is deeply intertwined with research on motion sickness, such that most theories applied to understand VR sickness were originally developed to study motion sickness (Kennedy et al. 2010; Oman 1990, 2012; Reason and Brand 1975). Early studies often assessed motion sickness via optokinetic drums (De Kleyn 1948; Honrubia et al. 1968; Suzuki and Komatsuzaki 1962). Hollow cylinders were lowered around participants, and they were painted inside with varied shapes, patterns, and colors. The cylinder would be spun, and researchers often—but not exclusively—studied the visual elements that produced motion sickness (e.g., patterns, speed; Bonato et al. 2005; Bos and Bles 2004; Bubka et al. 2006). Once VR became widespread, optokinetic drum studies were assumed to generalize to VR sickness, as participants undergo similar procedures when studying motion and VR sickness (Bonato et al. 2004, 2009; Riecke et al. 2005). In both cases, participants remain stationary while observing visual movement, and any sickness is assumed to arise due to the disparity between visual movement and physical stationarity. Also, the symptoms of VR sickness are almost identical to motion sickness, giving researchers another justification to generalize findings of motion sickness to VR sickness (Kim et al. 2018; Takeuchi et al. 2018). Theories originally developed to understand motion sickness were—and still are—assumed to explain VR sickness for these reasons (Kennedy et al. 2010; Kim et al. 2018; Oman 1982, 1990, 2012).

Of theories applied to understand VR sickness, PIT is among the most supported (Li et al. 2018; Lim et al. 2018; Riccio and Stoffregen 1991; Stoffregen and Smart 1998). The theory proposes that a mismatch of perceived and expected information regarding movement and orientation between the visual and vestibular systems causes people to become unbalanced, and prolonged postural instability is the primary cause of motion sickness (Smart et al. 2002; Palmisano et al. 2018). PIT was built upon prior widespread motion sickness theories, including poison theory and sensory conflict theory. Like poison theory, PIT suggests that the body reacts with motion sickness (notably purging) because toxins otherwise cause such prolonged postural effects, and, like sensory conflict theory, PIT suggests that mismatches between perceptions and expectations of visual and vestibular cues is the cause of postural instability. PIT suggests a direct antecedent to motion sickness, postural instability, and it therefore lends itself to developing hypotheses and broader theoretical models. Riccio and Stoffregen (1991) further identified four provocative environments that produce motion sickness: low-frequency vibration, weightlessness, changing relations between gravitoinertial force vector and the surface of support, and altered specificity. Of these, altered specificity is the most relevant to VR sickness, and it refers to, "optically specified accelerations and rotations that are unrelated to the constraints on control of the body", wherein, "postural control strategies for gaining postural stability will not work" (LaViola 2000, p. 52). Thus, VR sickness is believed to emerge due to postural instability arising from visual/vestibular disparities, and contributing factors to postural instability susceptibility and/or disparity sensitivity are believed to promote VR sickness.

Many researchers have supported PIT, showing that postural control measured before starting the program is negatively related to subsequent VR sickness (Arcioni et al. 2019; Hemmerich et al. 2019; Munafo et al. 2017), and postural instability during the VR program is often observed before VR sickness is felt and correlated with the extent of VR sickness (Palmisano et al. 2018; Smart et al. 2002; Stoffregen et al. 2010; Villard et al. 2008). More recent research has applied increasingly complex research designs to support the tenets of PIT. Sugiura et al. (2018) supported that not only visual cues predict VR sickness, but making participants more or less aware of their postural instability can also influence VR sickness; Weech et al. (2018) supported that noisy vestibular stimulation via bone vibrations, which can produce sensations of movement, can reduce VR sickness when paired with associated visual movements; and Takeuchi et al. (2018) demonstrated that modulation of cortical excitability in the temporoparietal junction (which processes vestibular and visual information) via transcranial direct current stimulation reduces VR sickness. These cumulative findings have caused a paradigm shift towards greater acceptance of PIT as a plausible explanation of VR sickness.

Despite recurrent support, some authors have provided contradictory evidence against PIT, suggesting that postural instability and motion sickness are only common outcomes of sensory conflict (Akizuki et al. 2005; Dennison and D'Zmura 2017, 2018; Guerraz and Bronstein 2008). The theory is thereby not infallible, and it may benefit from refinement. We apply PIT to hypothesize relationships between individual differences and VR sickness due to its repeated application, and our discussion details how our results can be used to create such refinements. Because PIT suggests that the predictors of VR sickness contribute to postural instability and/or disparities between the visual and vestibular systems, we separate our hypotheses by individual differences that influence both, postural instability alone, disparities alone, and neither.

1.3 Hypothesis development

1.3.1 Postural instability and disparity hypotheses

We identify only one individual difference that relates to both postural instability and visual/vestibular disparities: motion sickness susceptibility. Motion sickness susceptibility refers to a person's proneness to becoming motion sick, and it has been shown to repeatedly predict VR sickness (Golding 2006; Treleaven et al. 2015). Typically, motion sickness susceptibility is measured via self-report scales that ask participants to indicate the frequency that they experience motion sickness in various scenarios (e.g., cars, boats, planes, trains). A person's tendency to systematically experience motion sickness may be due to either their susceptibility to postural instability and/or their sensitivity to visual/vestibular disparities, and therefore its influence on VR sickness may be due to either. Given the strong association between motion sickness and VR sickness, we propose that motion sickness susceptibility predicts VR sickness.

Hypothesis 1 Motion sickness susceptibility is positively related to VR sickness.

1.3.2 Postural instability hypotheses

We suggest four individual differences that may relate to VR sickness due to influences on postural instability. That is, these individual differences are believed to cause users to have more/less control over their postural stability and thereby experience less/more VR sickness. The first of these is gender. Women experience greater VR sickness compared to men, and, while several justifications have been proposed, differences in postural stability may be the most supported (Arcioni et al. 2019; Hemmerich et al. 2019; Munafo et al. 2017). Studies have shown that women overall experience greater postural sway when standing (Chiari et al. 2002; Era et al. 2006; Masui et al. 2005), and the increased VR sickness in women coincides with an increased magnitude of postural sway (Arcioni et al. 2019; Fransson et al. 2019; Munafo et al. 2017). Women are believed to be more susceptible to postural instability effects from differing visual and vestibular cues (such as using VR) because of their heightened postural instability in general, and it is therefore expected that they experience greater VR sickness than men.

Hypothesis 2 Gender is related to VR sickness, such that women experience more VR sickness than men.

While some authors consider age as a proxy for other predictors (e.g., technological experience), others have proposed substantive justifications for age's influence on VR sickness (Golding 2006; Nichols and Patel 2002; Owen et al. 1998). Older individuals experience greater postural sway than younger individuals, in part due to the deterioration of muscle strength associated with aging, and they may be less able to combat increases to postural instability due to visual/vestibular conflicts (Arns and Cerney 2005; Knight and Arns 2006; Treleaven et al 2015). In accordance with PIT, these increases to postural instability are associated with VR sickness, and older people are expected to experience greater VR sickness than younger people.

Hypothesis 3 Age is positively related to VR sickness.

While less frequently studied than gender or age, researchers have argued that users' amount of prior sleep—or lack thereof—influences VR sickness, which poses important implications for using VR early in the morning or late at night (Altena et al. 2019; Kolasinski and Gilson 1998). These authors cite prior research supporting that sleep is associated with postural sway; those who are well-rested exhibit less postural sway than those who are tired (Fabbri et al. 2006; Karita et al. 2006; Nakano et al. 2001). Like age and gender, this increased postural sway indicates that tired individuals may be less able to combat any increases to postural sway from visual/vestibular disparities, and tired individuals are expected to experience greater VR sickness. We predict that well-restedness predicts VR sickness.

Hypothesis 4 Well-Restedness is negatively related to VR sickness.

For decades, researchers and practitioners have supported that VR can improve physical rehabilitation program outcomes, and participants of these programs often possess a disabling neurological disorder (Howard 2017; Ravi et al. 2017; Rose et al. 2018; Tieri et al. 2018). Those with a neurological disorder, however, have less control over their physical capabilities (including postural stability), and they assumingly possess less ability to stabilize themselves when experiencing conflicting visual and vestibular information (such as using VR). It is therefore predicted that these individuals will likewise experience greater VR sickness.

Hypothesis 5 Possessing a neurological disorder is related to VR sickness, such that those possessing a neurological disorder are more likely to experience VR sickness.

1.3.3 Disparities hypotheses

We propose four individual differences that may relate to VR sickness due to experiencing or perceiving greater visual/vestibular disparities. That is, while these individual differences may not cause users to have more or less control over their postural stability, they may nevertheless relate to VR sickness because they cause users to perceive greater differences between their visual stimuli and physical movements. The first of these is real-world experience. Those with ample prior real-world experience performing a task are likely attuned to all features of the task. For instance, an expert pilot would expect specific vestibular senses when flying that a novice pilot may not anticipate. For this reason, those with more real-world experience may be more cognizant of any visual/vestibular disparities when performing the task in a VR environment, and, in accordance with PIT, they would subsequently experience greater postural instability and VR sickness (Rebenitsch and Owen 2014; Stein and Robinski 2012; Stoffregen et al. 2017). Because real-world experience is expected to correspond with a greater sense of visual/vestibular disparity, we expect real-world experience to predict VR sickness.

Hypothesis 6 Real-world experience is positively related to VR sickness.

Many authors have supported that technological experience relates to less VR sickness (Mittelstaedt et al. 2018; Rebenitsch and Owen 2014; Shafer et al. 2017; Zhang et al. 2016). These authors speculate that prior experience using the applied VR technologies is particularly effective for reducing sickness, but even prior experience using related technologies is beneficial. For instance, experiencing VR on a computer monitor may reduce VR sickness when using an HMD, although prior use of HMDs may be most effective at reducing sickness for future use of HMDs. PIT likewise suggests that people can become accustomed to visual/vestibular disparities. Observing visual movement in the absence of physical movement, for instance, can become unthreatening to humans if the stimuli is repeatedly observed, as expectations become aligned with the stimuli. The body begins to recognize the stimuli as a natural occurrence, and VR sickness no longer arises because the stimuli is no longer perceived as a disparity. Based on this theoretical support, we expect technological experience to predict motion sickness.

Hypothesis 7 Technological experience is negatively related to VR sickness.

Immersive tendencies refer to a person's predisposition to become engaged and feel present in digital environments (Buttussi and Chittaro 2017; Diemer et al. 2015; Slater 2018). When a user becomes fully present in their VR experiences, they perceive their digital environment as their actual environment and their digital body as their actual body (Diemer et al. 2015; Slater 2018). These users may even ignore cues from their physical bodies, such as their vestibular senses, and any visual experiences in the digital environment may no longer be cognitively matched with their vestibular senses. Because visual/vestibular disparities may no longer be realized, it is believed that those predisposed to feel fully present are less likely to experience VR sickness. We expect immersive tendencies to negatively relate to VR sickness.

Hypothesis 8 Immersive tendencies is negatively related to VR sickness.

While few authors have studied the relationship between visual acumen and VR sickness, sensory conflict theory and PIT have been used to hypothesize this relationship (Hale and Stanney 2006; Jacobs et al. 2019). Those with poorer eyesight are unable to observe finer details of their digital environment, and some are even unable to observe most details of their digital environments. In these cases, users with poor eyesight may be less aware of cues that indicate disparities between their visual and vestibular systems, and these users may experience less VR sickness. Thus, we expect visual acumen to predict VR sickness.

Hypothesis 9 Visual acumen is positively related to VR sickness.

1.3.4 Neither postural instabilities nor disparities hypotheses

Several individual differences have been studied alongside VR sickness with no theory suggested for their relationships, and PIT does not easily lend itself to explicating such relationships. The first of these is possessing a psychological disorder. Several authors have supported the efficacy of VR to deliver psychological therapies (Carl et al. 2019; Rauch et al. 2018; Zhang and Ho 2017). In some cases, authors recruit participants with and without psychological disorders to determine whether differences exist regarding their experiences with VR, including feelings of VR sickness (Farook et al. 2018; Reger et al. 2018). Resultant correlation matrices often include VR sickness and/or group comparisons are made regarding VR sickness, but no theory is provided regarding why possessing a psychological disorder is or is not related to VR sickness. Despite the lack of relevant theoretical support, we test the relationship of possessing a psychological disorder and VR sickness given its reporting in prior articles.

Research Question 1 Does a relationship exist between possessing a psychological disorder and VR sickness?

Many authors also have supported that VR can effectively reduce phobias (Botella et al. 2017; Morina et al. 2015; Riva et al. 2016). Some of these authors have likewise recruited participants with and without phobias to determine whether differences exist between the two populations regarding their experiences and perceptions of VR, and VR sickness is often measured. While theory is rarely provided for any resultant observations, we nevertheless test the relationship of possessing a phobia and VR sickness due to its prior reporting.

Research Question 2 Does a relationship exist between possessing a phobia and VR sickness?

Lastly, some authors have measured both VR sickness and cognitive abilities as control variables when testing VR programs for educational purposes. While a correlation has been reported for the two variables, theory has yet to sufficiently link them and PIT does little to predict any possible relationship. Thus, we test the relationship of cognitive ability and VR sickness due to prior popularity, rather than substantive predictions made by theory.

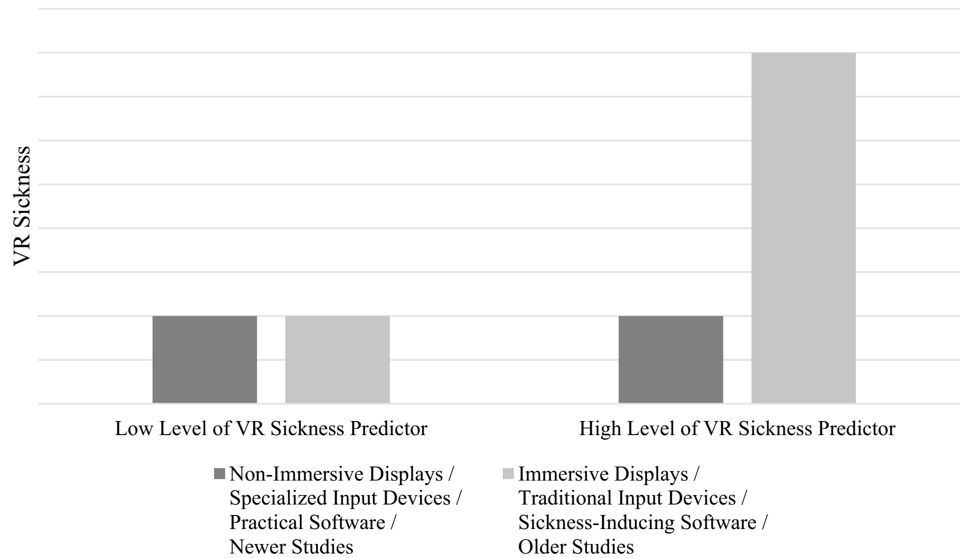
Research Question 3 Does a relationship exist between cognitive ability and VR sickness?

1.3.5 Moderation hypotheses

We test for several moderating influences that weaken or strengthen the relationships of the individual differences and VR sickness, which include aspects of the hardware, software, user, and even study source. While we still draw from PIT to do so, our usage of the theory is similar to applications of trait activation theory (TAT) (Mussel and Spengler 2015; Tett and Burnett 2003; Tett et al. 2013; Zagenczyk et al. 2017). TAT conceptualizes strong and weak situations. In strong situations, the context drives outcomes so strongly that any influence of individual differences is overpowered and potentially rendered null. In weak situations, the context has a smaller influence on outcomes, and the effects of individual differences are more apparent. TAT therefore proposes that the context moderates the relationship of individual differences and outcomes. We follow the same logic in the hypotheses below: we suggest that some applications of VR overpower any influence of individual differences on VR sickness, whereas other applications of VR allow the effects of individual differences to be more apparent. Figure 1 presents a visual representation of our moderation predictions.

The first tested moderating effect is the display hardware, specifically the comparison of non-immersive (e.g., computer monitor) and immersive (e.g., HMD, CAVE) hardware. Both types of hardware easily allow macro-breaks: breaks from the VR experience that last longer than a minute (Sharples et al. 2008; Treleaven et al. 2015). Users can walk away from a computer monitor and a CAVE, whereas they can remove a HMD. Compared to immersive displays, however, non-immersive displays more easily allow micro-breaks: breaks that last a few seconds (Lutz et al. 2017; Moss and Muth 2011; Sparto et al. 2004). When using a computer monitor, users can periodically look away from the screen if they feel symptoms of VR sickness, thereby alleviating such effects. Users may even do so subconsciously when VR sickness symptoms are subliminal, which prevents these

Fig. 1 Visual representation of moderation hypotheses



symptoms from becoming distressing (Akiduki et al. 2003; Ebenholtz 1992). When using a CAVE or HMD, it is much harder to take micro-breaks. Because the VR environment is immersive, users sometimes cannot look away, and they must remove themselves entirely from the experience or close their eyes.

Due to these differences in micro-breaks, it is expected that individual differences will have a weaker relationship with VR sickness when non-immersive displays are applied compared to immersive displays. When using a non-immersive display, those more likely to experience VR sickness have a greater opportunity to reduce such effects, and therefore both those who are not susceptible and those who are susceptible will experience low levels of VR sickness. When using an immersive display, those more likely to experience VR sickness have less opportunity to reduce such effects; those who are not susceptible will experience low levels of VR sickness, whereas those who are susceptible will experience high levels of VR sickness.

Hypothesis 10 The display hardware moderates the relationships between individual differences and VR sickness, such that their relationships are stronger when immersive displays are applied rather than non-immersive displays.

The choice of input hardware may too influence the relationships of VR sickness, specifically the choice of traditional (e.g., keyboard and mouse) or specialized (e.g., motion sensors) input hardware. Most often, specialized input devices are used to increase the fidelity of a VR program (Aggarwal et al. 2006; McMahan et al. 2012). For instance, multiple authors have developed faux welding tools with digital sensors to provide natural input, movements, and feedback during a VR welding training (Fast et al. 2004; Mavrikios et al. 2006; Stone et al. 2011). By using these input devices, the digital environment may become more aligned with the physical environment, and users may perceive fewer visual/vestibular disparities. We suggest that individual differences will have weaker relationships with VR sickness when specialized input hardware are applied compared to traditional input hardware. When using specialized input hardware, those more likely to experience VR sickness may be alleviated by the natural input design, and therefore both those who are susceptible and those who are not susceptible will experience low levels of VR sickness. When using a traditional input hardware, those more likely to experience VR sickness may be more cognizant of the visual/vestibular disparity due to the input design; those who are not susceptible will experience low levels of VR sickness, whereas those who are susceptible will experience high levels of VR sickness.

Hypothesis 11 The input hardware moderates the relationships between individual differences and VR sickness, such that their relationships are stronger when traditional input devices are applied rather than specialized input devices.

We also consider the moderating effects of the VR software. In current studies of VR sickness, two types of software are applied: software intended to induce VR sickness and practical software. Sickness-inducing software often presents visual stimuli similar to an optokinetic drum, such that certain patterns and shapes rotate around the user (De Kleyn 1948; Honrubia et al. 1968; Hu et al. 1991; Suzuki and Komatsuzaki 1962), whereas practical software intends to achieve a goal (e.g., education, therapy). We predict that individual differences have weaker relationships with VR sickness when practical software is applied compared to sickness-inducing software. When using practical software, the environment may be designed to reduce VR sickness, and both those who are not susceptible and those who are susceptible may experience low levels of VR sickness. When using sickness-inducing software, those more likely to experience VR sickness have fewer alleviating elements, and their natural proclivities will have a stronger effect; those who are not susceptible will experience low levels of VR sickness, whereas those who are susceptible will experience high levels of VR sickness.

Hypothesis 12 The software moderates the relationships between individual differences and VR sickness, such that their relationships are stronger when software intended to produce sickness is applied rather than practical software.

Many meta-analyses use the source year to represent technological sophistication, as applied technologies are expected to continuously improve from year to year (Cavanaugh 2001; Tamim et al. 2011). We do the same in the current meta-analysis. While many aspects of VR hardware and software may differ in these early and later studies, we assert that researchers and practitioners have been continuously seeking approaches to reduce VR sickness (Cobb et al. 1999; Hettinger and Riccio 1992; Kennedy et al. 1992a, b). It is expected that earlier studies on VR applied hardware and software that contained fewer elements to combat VR sickness, whereas more recent studies utilized prior research and implemented features to reduce VR sickness. We propose that individual differences will have weaker relationships with VR sickness as the source year increases. In more recent studies, the applied hardware and software may include many features to reduce VR sickness, and both those who are not and those who are susceptible may experience low levels of VR sickness. In older studies, the applied hardware and software may include fewer of these features; those who are not susceptible will experience low levels of VR sickness, whereas those who are susceptible will experience high levels of VR sickness.

Hypothesis 13 The source year moderates the relationship of the individual differences and VR sickness, such that the relationships between individual differences and VR sickness becomes weaker as the source year increases.

Lastly, authors have assessed the predictors VR sickness using an array of populations, including children, college students, adults, and others. No author has suggested that one of these populations are particularly resistant or susceptible to VR sickness. We likewise do not make any prediction regarding the moderating effect of population on the relationships of individual differences and VR sickness, but we nevertheless test this effect.

Research Question 4 Does the participant population moderate the relationships of individual differences and VR sickness?

2 Methods

Meta-analyses provide holistic results regarding a research domain (e.g., overall relationships) as well as specific results regarding a subset of studies (e.g., non-immersive display only, immersive display only). Meta-analyses can also compare relationships for different subsets of studies, permitting tests of moderation. We therefore perform a meta-analysis because it can effectively test each of our hypotheses and research questions. We followed the Meta-Analysis Reporting Standards (MARS) and Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to perform and report our meta-analysis (Appelbaum et al. 2018; Kepes et al. 2013; Levitt et al. 2018; Moher et al. 2009, 2015).

2.1 Identifying and coding sources

Searches were conducted in March 2019 in the EBSCO and Google Scholar databases using the following terms: virtual reality-induced symptoms and effects, “virtual reality” sickness, “simulator sickness”, and cybersickness. EBSCO searches return results that are aggregated from multiple other databases, including Academic Source Complete, Business Source Complete, MEDLINE, and PsycINFO. Google Scholar searches are more comprehensive than other academic databases, but it is also more likely to produce tangentially related results. For example, a search of “simulator sickness” produces 897 results in EBSCO, but it produces 11,000 results in Google Scholar. For this reason, we only included the first 1000 results of our Google Scholar searches in our database. Results beyond the first several hundred were largely irrelevant to the meta-analysis (e.g., only included term in references), and our decision to only record the first 1000 results of each Google Scholar search was supported.

These searches resulted in 3325 initial sources, which were coded by two coders in each subsequent phase (Fig. 2). The coders constructed coding guidelines, developed a rulebook, reviewed material, and trained each other on the coding rules. In the first two phases, the two coders initially coded articles together until they reached an agreement level of .80 (ICC[2,k]) for a set of 50 articles, and they then coded articles independently. In the third phase, both coders coded each article and conferred on any disagreements. Prior guides were followed to determine coding procedures

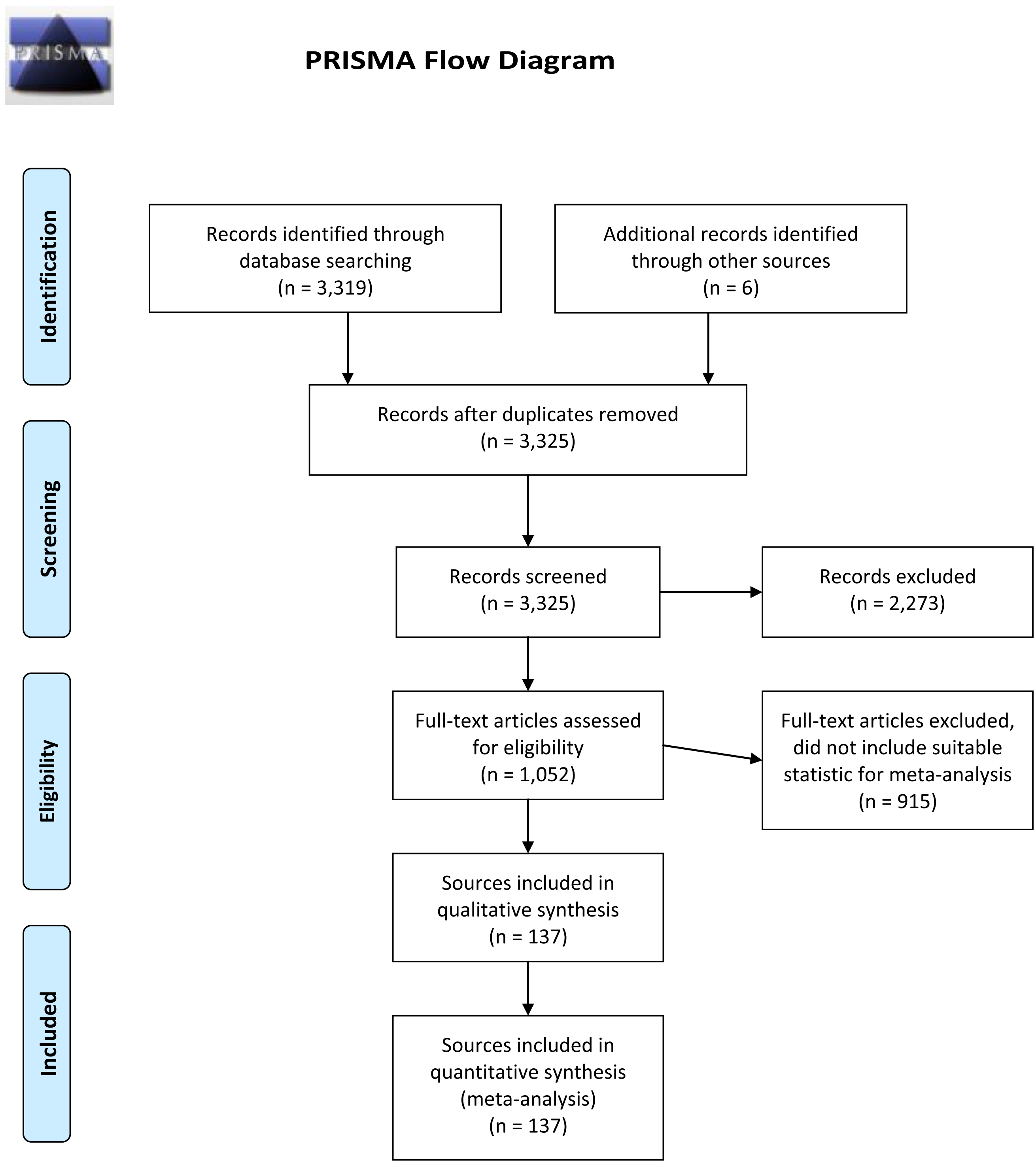


Fig. 2 PRISMA flow diagram

(Borenstein et al. 2011; Hedges and Olkin 2014; Moher et al. 2015).

In the first phase, the coders coded whether each source (a) administered a measure of VR sickness after participants used a VR program and (b) reported quantitative statistics. This reduced the initial list of 3325 sources to 1052. In the second phase, the coders coded whether each source reported a suitable statistic representing the relationship between VR sickness and an individual difference, which reduced the list from 1052 sources to 131. In this process, we also removed any sources that reported effect sizes found in a different source, such as an article reporting the same results as a dissertation. We also did not include effect sizes that represent the relationship of more than two variables, such as partial correlations or ANCOVA, due to previously detailed concerns regarding their biasing influence in meta-analyses (Boxer et al. 2015; Ferguson 2015; Furuya-Kanamori and Doi 2016; Rothstein and Bushman 2015).

In the third phase, both coders coded each relevant effect size and moderator variable from these sources. The authors contacted the corresponding authors of each source for any unpublished results, and any provided results were included in the current analyses. These procedures resulted in a final meta-analytic database of 137 sources and 149 studies.

Lastly, we clarify our PICOS approach (participants, interventions, comparators, outcomes, and study designs; Moher et al. 2009). First, we included studies with all types of participant populations, as we compared differences in study results based on these populations. Second, we also included studies with all types of VR interventions, as we also compared differences in study results based on the applied hardware and software. Most of these studies only applied a single type of VR intervention, and then analyzed the relation of individual differences and VR sickness in the context of this one VR intervention. Some compared two or more VR interventions, and then separately provided the relation of individual differences and VR sickness for each of the VR interventions. Third, we included studies with all types of comparators, including studies that did not have a comparator whatsoever. Fourth, while we only included studies that measured VR sickness after participants used a VR program, we included studies that used any type of self-report measure of VR sickness. Fifth, we included all types of studies that investigated VR sickness after participants used a VR program, whether it was a randomized trial, single-group trial, or any other type of research design.

2.2 Source and study attribute coding

Display Hardware We coded whether the applied VR program used traditional display hardware (computer monitor) or immersive display hardware (e.g., HMD, CAVE). If the authors did not state the display hardware, then it was assumed that a traditional display was used.

Input Hardware We coded whether the applied VR program used traditional input hardware (keyboard, mouse, and/or joystick) or specialized input hardware (e.g., motion sensor). If the authors did not state the input hardware, then it was assumed that traditional input was used.

Type of Program We coded whether the applied VR program was intended for practical purposes (e.g., training, therapy) or to induce sickness. Programs meant to induce sickness replicated a roller coaster or displayed sickness-inducing patterns in the digital environment.

Participant Population We coded whether the participant population were children/teenagers, which were 18 years of age or under and not enrolled in college; college students, which were enrolled in college; adults, which were 18 years of age or above and not enrolled in college; and special, which had a unique defining characteristic (e.g., brain injury, neurological disorder).

Source Type We coded whether the source was an unpublished research report, conference paper, thesis/dissertation, book chapter, or journal article.

Year We coded the year in which the source was published or completed.

3 Analyses

We first calculated indices of publication bias, including fail-safe k, Egger's test, trim-and-fill method, and weight-function model analysis. Fail-safe k determines the number of undiscovered null results to be included before the observed effect is not statistically significant (Carson et al. 1990). Egger's test estimates the relationship between the studies' effect sizes and their standard errors (Deeks et al. 2005), wherein a significant Egger's test indicates that studies with small samples have larger effects than studies with large samples. In this case, publication bias would be observed in the dataset. The trim-and-fill method estimates the number of studies missing from the right and left of the average meta-analytic effect based on observed effect sizes and standard deviations, and a large number of estimated missing studies indicates that publication bias exists in the dataset (Duval and Tweedie 2000). The weight-function model analysis indicates whether certain p value intervals were more or less likely to be observed, and the greater likelihood of certain intervals indicates that publication bias is present (Sutton et al. 2000). We also tested for outliers and influential cases. We calculated eight different indicators but primarily focused on studentized deleted residuals, Cook's distance, and covariance ratios.

All effects were converted to a common statistic and calculated via Comprehensive Meta-Analysis V3. All results are reported as correlation coefficients (r), which were calculated using a random-effects model. Multiple effects from the same study were averaged together to prevent unequal weighting, but Supplemental Material A includes all analyses reproduced via a three-level meta-analytic approach due to concerns about averaging effects together. This approach adopts a multilevel framework to account for variances within and between studies when calculating estimates, thereby eliminating the need to average effect sizes together from the same study. Because these results did not produce differing inferences from the primary analysis, we report the traditional analyses in the primary text and include the three-level analyses as a sensitivity analysis, which is the replication of meta-analytic results using alternative approaches to ensure that observations are not due to analysis decisions. The moderator analyses can also be interpreted as a sensitivity analyses, as these analyses indicate whether the current results are consistent when restricting analyses to certain technologies, populations, and beyond.

We also chose not to correct for unreliability. The most popular measure of VR sickness was the Simulator Sickness Questionnaire (SSQ; Kennedy et al. 1992a, b; Kennedy et al. 1993). Very few authors report the reliability of this measure, perhaps because prior research has argued that the SSQ is a formative rather than reflective measure. If true, then internal consistency may not be an appropriate indicator of unreliability for the measure, and correcting for unreliability may overestimate observed relationships. Furthermore, many of the individual differences studied in the current meta-analysis are either observed variables (e.g., age, gender) or almost exclusively measured via single-item measures (e.g., well-restedness, real-world experience). The relationships of these individual differences cannot be corrected for unreliability. Therefore, we believed it was inappropriate to correct for unreliability for only a small portion of relationships (and increase their strength), as our discussion qualitatively compares these relationships to identify the more proximal predictors of VR sickness.

To analyze the effects of source and study attributes, meta-analytic estimates were calculated separately by each level of the source/study attribute, and the confidence intervals of the levels were compared. We also calculated meta-regressions, in which a single attribute was included as the sole predictor for each combination of attributes and relationships. A statistically significant coefficient indicates a significant moderating effect. Lastly, data used for the current analyses are provided in a.zip folder entitled Supplemental Material B.

4 Results

We first provide descriptive information regarding our 149 obtained studies. Regarding the characteristics of the hardware and software, 125 sources utilized an immersive display, whereas 24 utilized a monitor; 91 utilized a specialized input device, whereas 58 utilized a keyboard, mouse, and/or joystick; and 141 utilized programs intended for practical purposes, whereas 8 utilized programs intended to produce VR sickness. Regarding participant characteristics, 38 sources utilized college student participants, 74 utilized adult participants, 32 used participants from a special population, 2 used child participants, 2 used participants from multiple populations, and 1 did not provide information regarding their sample. The average age of the participants was 31.53 with a standard deviation of 15.30, and the samples were well represented between men and women (56% male). Lastly, 90 of the sources were articles, 26 were conference presentations, 15 were dissertations or theses, 11 were unpublished research reports, 6 were provided unpublished data, and 1 was a book chapter. Together, these results suggest that our meta-analytic database was quite diverse regarding the applied hardware and software, participant population, and types of sources—supporting the thoroughness of our search and coding procedures.

4.1 Publication bias results

Fail-safe *k*, Egger's test, and the trim-and-fill method results are provided in Table 2. Weight-function analyses as well as outlier and influential case results are provided in Supplemental Material A. The fail-safe k was sufficiently large for all significant primary analyses (35–3434), indicating that many non-significant studies would need to be discovered for these results to be notably swayed. Egger's test was significant for only one relationship (well-restedness); the trim-and-fill method identified a large number of missing studies (> 1) for one relationship (age); and the weight function analysis was significant for one relationship (gender). When further investigating these instances of possible publication bias, age and gender each had one study with a large, positive effect size and small precision. These studies may have caused the trim-and-full method as well as weight function analysis to interpret that studies were missing on the opposite side of the mean, as no studies were observed with similar negative effect sizes and precisions. We chose to retain these studies for three reasons.

First, the applied random effect meta-analytic model is resilient to influential cases, and the outlier studies had small sample sizes. These studies therefore had a small effect on all observed results. Second, no relationship was considered to contain publication biases by more than one analysis. The sporadic nature of the results cannot confirm that publication biases are present in these analyses, and they also suggest that any possible publication biases in the primary analyses are small. Third, our inferences remained consistent when reanalyzing these relationships while excluding these possible influential cases. For this reason, we chose to be conservative in our analytic decisions and retain as many sources as possible. These publication bias results are not concerning, but readers should interpret the primary results with these possible biasing influences in mind for well-restedness, age, and gender.

Table 2 Publication bias analysis results

Individual difference	I^2	k	Fail safe k	Egger's test β_0	Egger's test t	Implied missing	
						Left of mean	Right of mean
(1) Motion sickness susceptibility	32.76	45	3434	− .07	.21	0	0
(2) Gender	51.82	48	1517	.73	1.24	0	0
(3) Age	47.53	30	2	− .22	.37	10	0
(4) Well-restedness	69.62	6	0	3.36	3.53*	1	0
(5) Neurological disorder	71.71	12	35	− .64	.21	1	0
(6) Real-world experience	78.30	14	74	− .80	.65	0	0
(7) Technological experience	67.17	22	65	1.06	1.38	0	0
(8) Immersive Tendencies	73.62	6	0	− .68	.26	0	1
(9) Visual Acumen	83.77	4	0	6.71	3.77	0	0
(10) Psychological disorder	88.97	6	0	5.55	2.09	0	0
(11) Relevant phobia	24.55	11	142	.02	.03	0	1
(12) Cognitive abilities	57.65	5	0	.77	.30	0	0

* $p < .05$

Table 3 Primary meta-analytic results

Individual difference	# of sources	k	n	r	95% CI	Z value	p
(1) Motion sickness susceptibility	39	45	3915	.33	.28, .37	14.24	**< .001**
(2) Gender	43	48	3048	.21	.16, .26	7.76	**< .001**
(3) Age	24	30	1873	.04	− .03, .11	1.13	.26
(4) Well-restedness	6	6	751	.05	− .11, .20	.57	.57
(5) Neurological disorder	10	12	391	.19	.01, .36	2.03	**.04**
(6) Real-world experience	13	14	1295	.14	.01, .27	2.03	**.04**
(7) Technological experience	19	22	1641	− .10	− .20, − .01	− 2.08	**.04**
(8) Immersive tendencies	6	6	496	.06	− .13, .24	.59	.56
(9) Visual acumen	4	4	173	.15	− .26, .51	.72	.47
(10) Psychological disorder	6	6	388	.17	− .15, .46	1.04	.30
(11) Relevant phobia	10	11	784	.29	.21, .38	6.37	**< .001**
(12) Cognitive abilities	5	5	264	− .08	− .28, .12	− .80	.42

Bolded numbers indicate p-values less than .05

4.2 Primary analysis results

Our primary results are presented in Table 3. To interpret the meta-analytic results, we applied recent effect size guidelines for the relationships of individual differences (Bosco et al. 2015; Gignac and Szodorai 2016; Paterson et al. 2016). We first tested the one effect associated with both postural instability and visual/vestibular disparities, motion sickness susceptibility. Motion sickness susceptibility had a large and positive relationship with VR sickness ($\bar{r}$ = .33, 95% CI [.28, .37], $p < .001$), supporting Hypothesis 1.

We then tested four effects associated with postural instability: gender, age, well-restedness, and possessing a neurological disorder. The results supported that women suffer more VR sickness than men ($\bar{r}$ = .21, 95% CI [.16, .26], $p < .001$), and the effect was moderate in size. Possessing a neurological disorder also had a moderate and positive relationship with VR sickness ($\bar{r}$ = .19, 95% CI [.01, .36], $p = .04$), whereas age ($\bar{r}$ = .04, 95% CI [− .03, .11], $p = .26$) and well-restedness ($\bar{r}$ = .05, 95% CI [− .11, .20], $p = .57$) did not have significant relationships with VR sickness. These results support Hypotheses 2 and 5, but they fail to support Hypotheses 3 and 4.

We also tested four effects associated with experiencing a greater disparity between visual and vestibular systems: real-world experience, technological experience, immersive tendencies, and visual acumen. Relevant real-world experience had a positive and small relationship with VR sickness ($\bar{r}$ = .14, 95% CI [.01, .27], $p = .04$), whereas technological experience had a negative and small relationship with VR

Table 4 Summary of moderator analysis results

	Display hardware	Input hardware	Type of program	Participant population	Source type	Year
(1) Motion sickness susceptibility			Statistically significant		RR-D, D-A	
(2) Gender			Statistically significant	C-CS, C-A, C-S	PR-C, PR-D, PR-A	
(3) Age					RR-D	
(4) Well-restedness						
(5) Neurological disorder						
(6) Real-world experience					D-A	
(7) Technological experience				C-S, CS-S, A-S		
(8) Immersive tendencies						
(9) Visual acumen				A-S		
(10) Psychological disorder	Statistically significant			A-S	C-A	
(11) Phobia						Statistically significant
(12) Cognitive abilities						Statistically significant

Entries for the Participant Population and Source Type columns represent significant comparisons via dummy-coded meta-regression

C children/teenagers, *CS* college students, *A* adult, *S* special participants, *PR* provided results, *RR* research report, *C* conference, *D* dissertation, *BC* book chapter, *A* Article

sickness ($\bar{r} = -.10$, 95% CI [$-.20$, $-.01$], $p = .04$). Immersive tendencies ($\bar{r} = .06$, 95% CI [$-.13$, .24], $p = .56$) and visual acumen ($\bar{r} = .15$, 95% CI [$-.26$, .51], $p = .47$) did not have significant relationships with VR sickness. These results support Hypotheses 6 and 7, but they fail to support Hypotheses 8 and 9.

Three effects not associated with a theoretical perspective were assessed: possessing a psychological disorder, possessing a phobia, and cognitive ability. Possessing a phobia had a large and positive relationship with VR sickness ($\bar{r} = .29$, 95% CI [.21, .38], $p < .001$), whereas possessing a psychological disorder ($\bar{r} = .17$, 95% CI [$-.15$, .46], $p = .30$) and cognitive ability ($\bar{r} = -.08$, 95% CI [$-.28$, .12], $p = .42$) did not have significant relationships with VR sickness.

We tested several moderating effects for each relationship. The full reporting of these results is presented in Supplemental Material C, whereas a summary is provided in Table 4. The results significantly differed based on the participant population for four of twelve effects, suggesting that the participant population may influence the magnitude and/or direction of the tested effects. Likewise, the results also significantly differed based on the source type for five of twelve effects, suggesting that the source type may also influence the magnitude and/or direction of the tested effects. On the other hand, only one of twelve effects significantly differed when comparing results obtained via non-immersive displays and immersive displays, indicating that the display hardware was not a consistent moderator. Zero of twelve effects significantly differed when comparing results obtained via traditional input and specialized input, indicating that the input hardware was not a consistent moderator. Only two of twelve effects significantly differed when comparing results obtained via practical software and sickness-inducing software, suggesting that the type of program was not a consistent moderator. Again, only two of twelve effects had a significant relationship with source year, indicating that the year was not a consistent moderator. Hypotheses 10, 11, 12, and 13 were not supported.

Lastly, we provide two sets of supplementary analyses. First, we chose to provide additional information regarding two relations due to their theoretical importance: motion sickness susceptibility and gender. Forest plots for these two relations are provided in Figs. 3 and 4, respectively. Some variation was evident in effects observed within prior sources, which is also reflected in the I^2 values of 32.762 and 51.823 for motion sickness susceptibility and gender, respectively. This I^2 value for motion sickness susceptibility indicates a relatively small amount of heterogeneity in effects, but the I^2 value for gender indicates moderate heterogeneity (Higgins et al. 2019). While the more specific analyses at

Study name	Subgroup within study	Outcome	Statistics for each study				
			Correlation	Lower limit	Upper limit	Z-Value	p-Value
Treleaven et al., 2015	Study 1	Combined	-0.288	-0.562	0.043	-1.712	0.087
Mittelstaedt et al., 2018	Study 2	Combined	0.020	-0.426	0.459	0.083	0.934
Warner, 1993	Study 1	Combined	0.080	-0.662	0.743	0.179	0.858
Warner, 1993	Study 2	Combined	0.093	-0.422	0.563	0.338	0.736
Kolndorfer, 2009	Study 1	Outcome A	0.098	-0.372	0.528	0.395	0.693
Stanney et al., 1999	Study 1	Outcome A	0.110	-0.237	0.432	0.615	0.539
Reason & Diaz, 1971	Study 1	Combined	0.125	-0.414	0.599	0.436	0.663
Rebenitsch & Owen, 2014	Study 1	Combined	0.145	-0.318	0.552	0.601	0.548
Chu et al., 2013	Study 1	Combined	0.152	-0.390	0.617	0.532	0.595
Yaqub, 2018	Study 1	Combined	0.178	-0.331	0.607	0.672	0.501
Nichols et al., 2000	Study 1	Combined	0.206	0.076	0.329	3.083	0.002
Gower & Fowlkes, 1989b	Study 1	Combined	0.215	0.005	0.407	2.003	0.045
Johnson, 2007	Study 1	Combined	0.216	0.072	0.351	2.916	0.004
Gower et al., 1987	Study 1	Outcome A	0.240	0.069	0.398	2.726	0.006
Kennedy et al., 1992	Study 2	Combined	0.242	0.108	0.367	3.504	0.000
Rebenitsch, 2015	Study 1	Combined	0.246	-0.106	0.544	1.377	0.168
Nichols, 2000	Study 1	Outcome A	0.250	0.029	0.448	2.212	0.027
Kennedy et al., 1992	Study 1	Combined	0.273	0.141	0.395	3.979	0.000
Flinton & White, 2009	Study 1	Combined	0.275	0.064	0.462	2.540	0.011
Braithwaite & Braithwaite, 1990	Study 1	Combined	0.282	0.091	0.453	2.855	0.004
Dennison et al., 2016	Study 1	Combined	0.307	-0.171	0.668	1.268	0.205
Gower & Fowlkes, 1989a	Study 1	Combined	0.319	0.113	0.498	2.990	0.003
Nesbitt et al., 2017	Study 1	Combined	0.328	-0.087	0.646	1.559	0.119
Kennedy et al., 2001	Study 1	Combined	0.352	0.288	0.413	10.161	0.000
Llorach et al., 2014	Study 1	Combined	0.356	0.178	0.511	3.794	0.000
Weech et al., 2018	Study 1	Outcome A	0.360	-0.000	0.638	1.958	0.050
Mittelstaedt et al., 2018	Study 1	Combined	0.361	-0.097	0.693	1.557	0.119
Treleaven, 2019	Study 1	Outcome A	0.362	0.175	0.524	3.676	0.000
Kennedy et al., 1988	Study 1	Combined	0.376	0.303	0.445	9.407	0.000
Matas et al., 2016	Study 1	Outcome A	0.400	0.015	0.682	2.032	0.042
McIntire, 2014	Study 1	Outcome A	0.403	-0.000	0.694	1.958	0.050
Kim et al., 2005	Study 1	Outcome A	0.426	0.195	0.612	3.465	0.001
Iskenderova et al., 2017	Study 1	Outcome A	0.430	0.089	0.681	2.434	0.015
Lampton et al., 1995	Study 1	Combined	0.444	0.214	0.627	3.599	0.000
Wilson & Kinsela, 2018	Study 1	Outcome A	0.450	0.100	0.701	2.471	0.013
Nalivaiko et al., 2015	Study 2	Outcome A	0.476	-0.101	0.814	1.638	0.101
Stone, 2017	Study 1	Outcome A	0.480	0.366	0.580	7.378	0.000
Zielasko et al., 2018	Study 1	Outcome A	0.496	0.184	0.717	2.980	0.003
Reason & Diaz, 1971	Study 2	Combined	0.501	0.007	0.799	1.986	0.047
Mittelstaedt et al., 2019	Study 1	Combined	0.529	0.260	0.722	3.581	0.000
Mittelstaedt et al., 2018	Study 3	Combined	0.539	0.127	0.793	2.488	0.013
Watson, 1998	Study 1	Combined	0.573	0.404	0.704	5.724	0.000
Dennison & D'Zmura, 2017	Study 1	Combined	0.607	0.138	0.854	2.441	0.015
Gavgani et al., 2018	Study 1	Outcome A	0.616	0.273	0.820	3.213	0.001
Nalivaiko et al., 2015	Study 1	Outcome A	0.660	0.171	0.888	2.507	0.012
			0.326	0.283	0.367	14.237	0.000

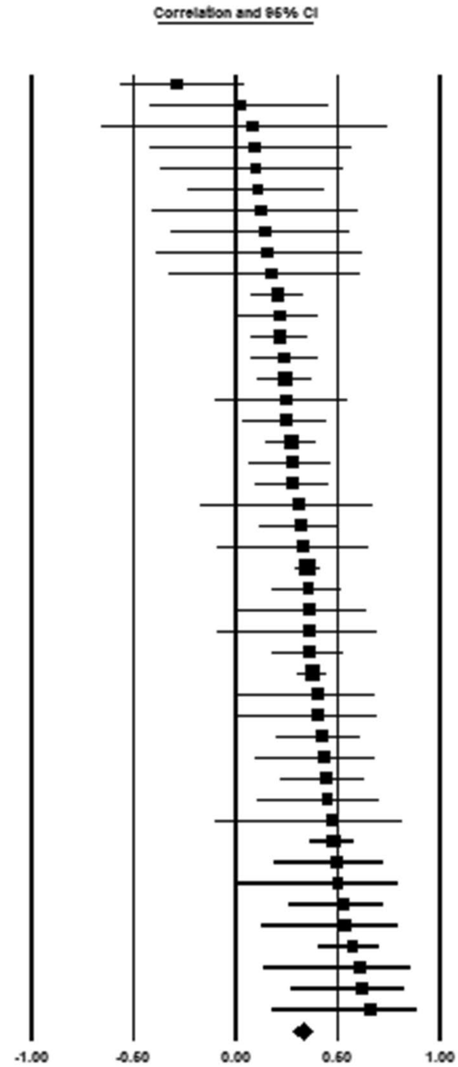


Fig. 3 Forest plot for the relation between motion sickness susceptibility and VR sickness

each level of the moderator (detailed below) reduced this heterogeneity (e.g., studies using immersive displays alone), it was still largely within the moderate range. This suggests that unidentified moderators may influence this relation and many others studied in the current meta-analysis, as evident by the I^2 values for all other relations provided alongside the publication bias results in Table 2.

Second, when coding our sources, we assumed articles that did not state their display hardware utilized a monitor and articles that did not state their input hardware utilized a keyboard and mouse. To ensure that such assumptions did not notably influence our results, we reconducted all moderator analyses of input and display hardware while excluding sources that did not explicitly state their applied hardware

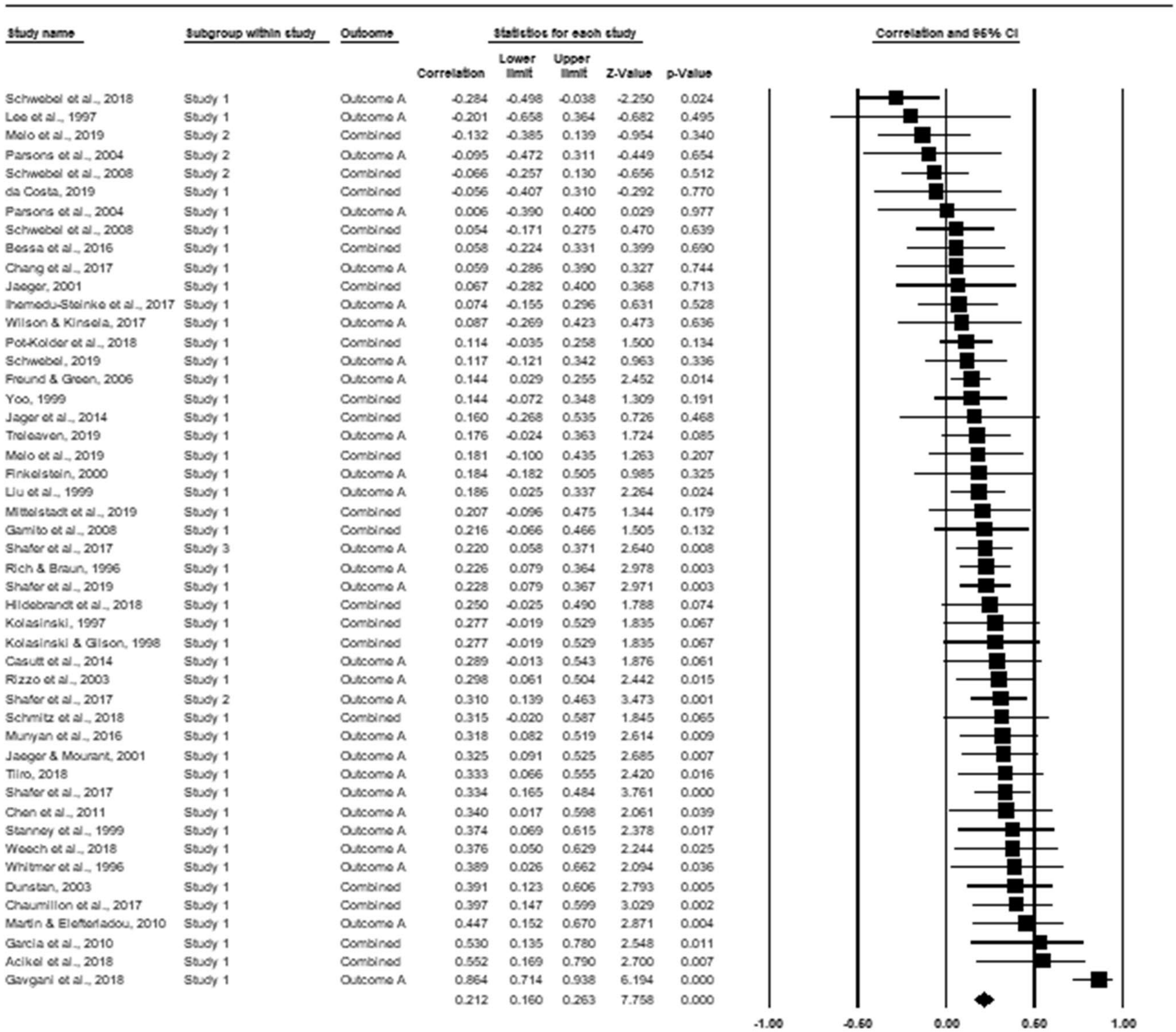


Fig. 4 Forest plot for the relation between gender and VR sickness

(Supplemental Material D), which serves as further sensitivity analyses. Only one of twelve analyses of moderation for display hardware differed, and only one of twelve analyses of moderation for input hardware differed. Even with these changes, neither display hardware nor input hardware were systematic moderators of our observed relations. Therefore, these supplemental analyses did not change any inferences made from the primary analyses, and Hypotheses 10 and 11 were still not supported.

5 Discussion

The relationship of individual differences with VR sickness is a dire concern for the present and future application of VR. To assess the validity of this concern, we conducted a meta-analysis investigating the effect of 12 individual differences on VR sickness, and we also tested several moderating effects. We applied PIT to develop hypotheses, which suggested that the individual differences may

Table 5 Summary of current findings

Hypothesis or research question	Finding	Conclusion
H1: Motion sickness susceptibility is positively related to VR sickness	$\bar{r} = .33, p < .001$	Supported
H2: Women experience more VR sickness than men	$\bar{r} = .21, p < .001$	Supported
H3: Age is positively related to VR sickness	$\bar{r} = .04, p = .26$	Not supported
H4: Well-restedness is negatively related to VR sickness	$\bar{r} = .05, p = .57$	Not supported
H5: Those possessing a neurological disorder are more likely to experience VR sickness	$\bar{r} = .19, p = .04$	Supported
H6: Real-world experience is positively related to VR sickness	$\bar{r} = .14, p = .04$	Supported
H7: Technological experience is negatively related to VR sickness	$\bar{r} = -.10, p = .04$	Supported
H8: Immersive tendencies is negatively related to VR sickness	$\bar{r} = .06, p = .56$	Not supported
H9: Visual acumen is positively related to VR sickness	$\bar{r} = .15, p = .47$	Not supported
R1: Does a relation exist between possessing a psychological disorder and VR sickness?	$\bar{r} = .17, p = .30$	Not significant
R2: Does a relation exist between possessing a phobia and VR sickness	$\bar{r} = .29, p < .001$	Significant
R3: Does a relation exist between cognitive ability and VR sickness	$\bar{r} = -.08, p = .42$	Not significant
H10: Display hardware moderates the relation between individual differences and VR sickness	1 of 12 Relations	Not supported
H11: Input hardware moderates the relation between individual differences and VR sickness	0 of 12 Relations	Not supported
H12: Software moderates the relation between individual differences and VR sickness	2 of 12 relations	Not supported
H13: Source year moderates the relation between individual differences and VR sickness	2 of 12 relations	Not supported
R4: Does the participant population moderate the relation of individual differences and VR sickness?	4 of 12 relations	Significant

H hypothesis, *R* research question

predict VR sickness due to their association with postural instability, sensitivity to visual/vestibular disparities, or both. We also drew from PIT to identify potential moderators in a similar manner to TAT, identifying strong and weak situations.

Table 5 provides a summary of our findings. Our results support that motion sickness susceptibility, the one individual difference associated with both postural instability and visual/vestibular disparities, is strongly related to VR sickness. Two of four effects associated with postural instability, gender and possessing a neurological disorder, are moderately related to VR sickness, and two of four effects associated with a sensitivity to visual/vestibular disparities, relevant real-world experience and technological experience, are weakly related to VR sickness. One effect associated with neither is also strongly related to VR sickness, possessing a phobia. The remaining individual differences did not have significant relationships with VR sickness: age, well-restedness, immersive tendencies, visual acumen, possessing a psychological disorder, and cognitive abilities. Further, two moderators had partially reoccurring effects, participant population and source type. Display hardware, input hardware, type of program, and source year did not have recurrent moderating effects, suggesting that relationships of individual differences with VR sickness are resilient across applications of VR. Below, we discuss the theoretical and practical implications of these findings, followed by a consideration of the present limitations.

5.1 Theoretical implications and future research directions

No category of antecedent produced decisively more reliable effects, but the effects did vary in size between the categories. That is, the significant effect associated with both postural instability as well as visual/vestibular disparities was large in magnitude, significant effects associated with postural instability were moderate in magnitude, and significant effects associated with visual/vestibular disparities were small in magnitude. This pattern of results supports PIT. PIT proposes that postural instability is a direct antecedent of VR sickness, whereas visual/vestibular disparities influence VR sickness via its effect on postural instability (Dennison and D'Zmura 2017; Koshlucher et al. 2016; Li et al. 2018; Lim et al. 2018). Based on this theory, individual differences that impact a more immediate influence on VR sickness, postural instability, would be expected to have larger effects than individual differences that impact a less immediate influence on VR sickness, visual/vestibular disparities. Thus, the predictions made by PIT were supported, and individual differences associated with postural instability should be expected to have larger relationships with VR sickness than individual differences associated with visual/vestibular disparities.

At the same time, it should be questioned why the same number of individual differences within these categories produced significant effects, rather than the more immediate category producing more. We suggest that the non-significant antecedents may have a weaker effect on their respective influence on VR sickness, and they ultimately produce smaller relationships with VR sickness. For instance, age and well-restedness may influence postural instability; however, their effects on postural instability may be quite weak, which would produce small effects on VR sickness. The same may be true for the non-significant individual differences associated with visual/vestibular disparities. If this is the case, postural instability may indeed be a more direct antecedent to VR sickness than visual/vestibular disparities, but their relationships with specific individual differences may vary. Given this possibility, it is important for future research to investigate the unsupported effects in the current article. High-powered studies may detect notable effects when studying these non-significant individual differences, as they may have significant albeit small influences on VR sickness. Alternatively, these same high-powered studies may not detect notable effects, and the scope of PIT may need to be reconsidered.

Among these investigations into null effects, we suggest that our non-significant findings regarding age are quite noteworthy. We predicted that older individuals would experience greater VR sickness because motor skills deteriorate in elderhood. Many of the included studies that investigated this relation obtained adult and elderly participants that represented a wide range of ages, adequately assessing this relationship for this specific age comparison. It is possible that age indeed does not have a significant relation with VR sickness, but it is also possible that prior studies have prioritized the weaker age comparison. That is, some authors have proposed that VR sickness is negatively correlated with age (Petri et al. 2020; Reis et al. 2016; Saredakis et al. 2020). Children develop finer motor skills until adulthood, and thereby they should experience greater VR sickness than adults due to differences in postural stability. Only one study investigated this relation in a child sample, and no studies included a sample of both children and adults. Therefore, the significance of age should not be entirely ruled out until more studies are performed with an adequate range of ages for this comparison. If this relation still produces a null effect, then the relation of age and VR sickness would cast doubts upon PIT.

In conducting these future studies on age, most VR developers recommend that the medium should be used only by those aged 12 and older (Aubrey et al. 2018). While this recommendation is largely due to the unknown effects of VR on young children, future research should explore detrimental outcomes of VR before further studies are conducted using children. Given the possibility of sensory mismatch when using VR, it is feasible that visual and vestibular development could be impaired of young children from experiencing VR too often.

Regarding further null effects, we assert that testing antecedents involving only a single sense, such as visual acumen, may provide important insights into PIT. Many of the tested antecedents, such as real-world and technological experience, involve sensitivities regarding many senses (Smart et al. 2002; Stoffregen and Smart 1998). For instance, a pilot with more flying hours may recognize improper physical, auditory, and visual cues in a VR flight simulator, and the relationship of real-world experience with VR sickness may be due to any of these systems; however, visual acumen was predicted to relate to VR sickness solely due to the failure to notice visual cues. The null effect of visual acumen suggests either (a) sensitivities to other sensory cues are stronger predictors of VR sickness than sensitivities to visual cues or (b) an improper visual cue is a strong situation and individual differences in sensitivities to visual cues are overridden by the overall effect of these cues. The current literature cannot determine whether either of these suggestions is more plausible, identifying a clear need for future research.

Perhaps more importantly, the current article proposed postural instability as well as visual/vestibular disparities as possible explanatory mechanisms, as guided by PIT, but we were unable to explicitly test any mediating effects. Further research is needed to test the mediators between individual differences and VR sickness. While PIT was partially supported in the current meta-analytic results, the proposed mechanisms may not be the actual link between individual differences and VR sickness. Some results have failed to support the theory (Akizuki et al. 2005; Dennison and D'Zmura 2017, 2018; Guerraz and Bronstein 2008), and research on these mediating mechanisms could provide a better perspective of the relationship between individual differences and VR sickness as well as a better understanding of PIT.

Furthermore, many individual differences have even more distal mediators proposed in prior research, and these distal mediators have themselves been suggested to influence postural instability and visual/vestibular disparities. Those with more relevant real-world experience have been proposed to better recognize disparities between the visual representations of digital environments and associated physical cues (or lack thereof) (Johnson 2007; Stoffregen et al. 2017). Task knowledge may therefore be a mediator between real-world experience and visual/vestibular disparities, but such an effect has not been tested in prior research. Similar sentiments could be expressed for other individual differences, and we call on future research to perform more nuanced investigations to test these potential mediating effects. In doing so, PIT could be linked to other theoretical frameworks associated with any supported mediators. For instance, if task knowledge is associated with visual/vestibular disparities, then learning theories could be integrated with PIT to identify further antecedents of VR sickness.

It should also be noted that, while the current article primarily applied PIT, our results also provide theoretical support for other theories related to VR sickness. Specifically, the development of PIT was largely based on poison theory and sensory conflict theory (Smart et al. 2002; Villard et al. 2008; Warwick-Evans et al. 1998). The current meta-analytic results likewise support the propositions of these theories, and future researchers should consider a renewed interest into investigating these and other theories of VR sickness.

One effect was significant without a justification provided in prior research: possessing a phobia. While made in a post hoc manner, we suggest a theoretical justification for this effect. Those who possess a phobia likely experienced notable anxiety before interacting with their VR environments, as these participants were typically participating in VR therapy programs to reduce their phobias (Carl et al. 2019; Morina et al. 2015). Anxiety has been previously supported to be associated with greater postural sway (Ohno et al. 2004; Wada et al. 2001), and those experiencing anxiety may be less capable of resisting influences on their postural stability—such as VR. It is therefore suggested that possessing a phobia is associated with VR sickness due to increases in anxiety and postural instability. This suggestion also aligns with the large strength of the effect, but future research is needed to support this post hoc justification.

Additionally, only two moderators produced somewhat consistent effects: participant population and source type. The source type is a common moderator in meta-analyses; published studies often report larger effects than unpublished studies. Researchers should interpret the current VR sickness literature with this limitation in mind. On the other hand, the participant population represents a potentially more substantive moderating effect. While most populations demonstrated that women experience more VR sickness than men, the relationship was reversed in children. Again, while made in a post hoc manner, it is possible that this moderating effect can be explained via postural instability theory. Because girls mature more quickly than boys, their physical capabilities likewise develop more quickly (Assaiante et al. 2005; Place and Englert 2003). Girls between the ages of 6 and 10 have been shown to have greater postural stability than boys between the same ages (Assaiante et al. 2005; Figura et al. 1991), and therefore girls may be more resistant to influences on postural instability than boys. While boys eventually gain more postural stability than girls in later years and thereby experience less VR sickness, the postural stability of girls in younger years may cause them to be more resistant to VR sickness. Similarly, some relationships differed between adult and special populations, suggesting that the relationships of individual differences and VR sickness may differ between these two populations. Future researchers should be cognizant that results regarding typical populations may not generalize to special populations—and vice versa. Further research is needed, however, to better understand each of these moderating effects.

Four moderators did not produce consistent effects, display hardware, input hardware, software type, and source year; however, the failure to support these moderators poses important implications. Authors have supported that certain technologies produce more VR sickness than others. For instance, HMDs are known to produce greater VR sickness than monitors (Merhi et al. 2007; Moss and Muth 2011; Sharples et al. 2008). The current results suggest that any VR sickness—no matter the technology—may still be predicted by relevant individual differences. Although a monitor may produce small amounts of VR sickness, these small amounts may be determined, in part, by the users' characteristics. While researchers and practitioners should continue developing technologies that produce less VR sickness, these results suggest that influence of individual differences will continue to be an important research topic.

It should also be noted that these moderators were hypothesized in a manner consistent with TAT, which proposes the existence of weak and strong situations. Because none of these moderators had consistent effects, it is possible that the conceptualization of weak and strong situations is not relevant for the study of VR sickness. Future research should therefore test whether the situation (e.g., hardware, software) can override the effect of other VR sickness predictors (e.g., individual differences) or whether the effects of the situation are largely independent from any other predictors of VR sickness.

Lastly, in performing these future studies, we recommend three important points of consideration. First, researchers should apply novel experimental designs to better infer causality between antecedent effects and VR sickness, particularly by testing theoretically supported approaches to reduce VR sickness. For instance, some authors have proposed that harnesses can reduce postural instability and subsequently reduce VR sickness (Golding et al. 2003; Manning and Stewart 1949; Ritchie et al. 2007). If such measures are effective for reducing sickness in certain populations, such as those with neurological disorders, then the explanatory mechanisms of VR sickness can be firmly supported. Second, researchers should test the boundaries of theory relevant to VR sickness, such as by testing antecedent effects not supported by theory. In doing so, researchers can determine whether these theories accurately discriminate between significant and non-significant antecedent effects, which is an important characteristic of useful theory. Third, most research on VR sickness is currently performed in the fields of engineering and human–computer interaction. We call for more researchers in psychology and biology to study VR sickness, as the phenomenon primarily involves psychological and biological mechanisms. These researchers could incorporate a wider array of relevant theory that may provide a more accurate understanding of VR sickness, and therefore the study of VR sickness should be more interdisciplinary.

5.2 Practical implications

Given these results, practical implications should likewise be noted. Practitioners must strongly consider the possible ramifications of unequal treatment when applying VR. Educators could disadvantage certain populations if VR is used as an educational medium without other opportunities to learn the material, as certain individuals may be unable to learn the material via VR due to VR sickness. Likewise, businesses must consider the unequal effects of VR sickness, especially towards protected groups. Organizations could produce adverse treatment if they use VR for training or selection purposes, as populations that experience greater amounts of VR sickness could learn less during a training and have their advancement hampered as well as perform worse for a selection test and become denied employment opportunities. The use of VR for training and selection purposes may need to be reconsidered until VR sickness can be reasonably eliminated across all subsets of users—or else organizations may risk costly lawsuits (Grabowski and Jankowski 2015; Howard and Marshall 2019). Approaches similar to the current handling of adverse impact may be required to determine acceptable amounts of unequal VR sickness when using VR for organizational purposes (Hough et al. 2001; Moscoso 2000).

In physical rehabilitation and psychological therapy contexts, however, practitioners may identify whether the medium can provide benefits to some subsets of the population. While equal treatment would be preferred, practitioners in these contexts must ensure that they are "doing the most good", which may include applying an effective treatment to certain subsets that should not be applied to others (Carl et al. 2019; Morina et al. 2015). Even disadvantaged users may receive greater benefits from VR interventions than alternative approaches. Although VR may produce elevated VR sickness for certain populations, it may still be more effective than other approaches for these at-risk people. Practitioners in these contexts may need to investigate the effectiveness of VR on a case-by-case or person-by-person basis.

From a safety perspective, individuals in high-risk industries, such as oil and gas, may utilize VR during their safety trainings (Sacks et al. 2013; Squelch 2001; Van Wyk and De Villiers 2009). VR can provide a realistic environment that would not be possible to encounter without serious consequences and financial costs. For instance, a simulated environment can be developed where beginner-level petroleum processing operators start the unit up, make a gasoline product that passes or exceeds federal specifications, and then shut the unit down. Due to risks and costs, this type of training is not provided until the operator reaches an advanced phase. If VR programs could mitigate some of the training costs while also providing real-world hazardous situations, the operators could have specialized safety training that is typically not readily available, and the employees could even begin developing their safety skills earlier in their training programs. Equal treatment would be preferred in these instances, similar to rehabilitation and therapy, but all users may be able to benefit from these simulations if they are able to save lives—even for those susceptible to VR sickness.

Lastly, the current results stress the necessity for organizations to develop programs that produce minimal VR sickness, else they risk disparate treatment in the workplace when utilizing VR. Prior studies have supported that reducing the display's size and minimizing movement in the digital environment can aid in reducing VR sickness (Fernandes and Feiner 2016; Jung et al. 2017). We urge organizations to review these studies and identify best practices for creating VR programs with minimal detrimental effects.

5.3 Limitations and additional future research directions

When performing a meta-analysis, methodological and analytic decisions must be made. Notably, we chose to aggregate studies across a wide array of contexts. While the representative studies for each calculated effect examined the same relation (e.g., gender and VR sickness), these studies were performed in varying contexts (e.g., adult populations, child populations). Such decisions can greatly influence the meta-analytic results. For example, meta-analyses are commonly critiqued for "comparing apples and oranges" by aggregating dissimilar studies together (Cortina 2003; Sharpe 1997), and some readers may be uncomfortable with calculating effects derived from differing contexts. For this reason, we urge readers to refer to the sensitivity analyses (Supplemental Material A, C, and D). These sensitivity analyses recalculate the current results using different methodological approaches, but they also provide analyses restricted to certain subsets of studies (e.g., adult populations alone). For instance, readers that consider VR to be solely media presented by immersive displays can refer to Supplemental Materials C and D for all analyses recalculated when only including studies that applied immersive displays. These focused results estimate the current relations of interest in isolated contexts, providing analyses that "only compare apples". We also include our data in Supplemental Material B, and readers can choose to replicate any analyses using different approaches to ensure the robustness of our results.

Meta-analyses are also bound to prior studies. While we identified several moderate and strong predictors of VR sickness, we may not have observed the individual differences that most strongly predict of VR sickness. It is possible that some strong effects have yet to be studied altogether, and therefore the current results should be regularly reinvestigated to incorporate more recent research—once such research has been conducted. Likewise, we underwent extensive efforts to discover all relevant studies, published and unpublished, that studied the relationships of individual differences and VR sickness. It is possible that studies were omitted from our analyses, and future researchers should consider other avenues to obtain relevant studies for any future meta-analyses on the same topic.

While the current meta-analysis was able to provide some specific information, such as the magnitude of effects in certain contexts, many nuanced research questions were unable to be tested. We did not test for mediating effects, although they are relevant for the assessment of PIT. Future research should look towards other approaches, such as experimental designs, to test these important research questions. Furthermore, meta-analyses are used to test relationships in a holistic manner, as done in the current article. Some authors, however, have applied PIT to provide detailed descriptions of more precise predictors and processes involved with VR sickness. For instance, some authors have investigated the differences in oscillation frequency and speed of visual stimuli in predicting VR sickness, whereas others have proposed specific processes involved in the habituation to conflicting sensory cues and VR sickness (Smart et al. 2002; Stoffregen and Smart 1998). While such in-depth investigations into a single relationship were beyond the scope of the current article, we nevertheless urge future authors to perform these focused investigations to further PIT. The results of the current meta-analysis can serve as a guide regarding specific relationships that should be tested further, notably individual differences that produced statistically significant overall effects on VR sickness.

While our I^2 values were typical for meta-analyses of VR and/or individual differences (Chesham et al. 2018; Fodor et al. 2018; Howard and Gutworth 2020; Merchant et al. 2014; Pletzer et al. 2019; Soutter et al. 2020; Zettler et al. 2020), some I^2 values indicated substantial heterogeneity in certain meta-analytic relations (Higgins et al. 2019; Higgins et al. 2003), which suggests that unidentified moderators may influence these relations. For this reason, we provide I^2 values for each tested relation in each condition of the moderating variables. For instance, we provide the I^2 value for the relation of age and VR sickness when only including sources that applied immersive displays alone. Readers can refer to these I^2 values to identify relations that may possess unexplained heterogeneity, and then perform studies to identify sources of this heterogeneity. That is, while these subgroup analyses reduced the observed heterogeneity in many instances, it did not reduce it enough to suggest that minimal heterogeneity exists for most studied relations. Therefore, these observations should spark many future studies investigating moderating influences on the relations between individual differences and VR sickness.

Similarly, we also assumed that all technologies within a category of the moderators were homogeneous. That is, we assumed that applied HMDs were similar enough to be meaningfully grouped together and analyzed as moderators. Future research should consider differentiating the types of HMDs based on various characteristics (e.g., resolution quality) and performing more nuanced analyses via these more specific moderators. This is especially important considering that certain HMD characteristics have been suggested to reduce VR sickness (e.g., field-of-vision). Such analyses may need to be conducted, however, only after additional studies on the topic have been completed, as doing so would require a large dataset of existing sources.

Lastly, we assumed that certain moderators were not practically significant because they did not moderate more than two relationships, and these moderators included display hardware, input hardware, type of program, and source year. It is possible, however, that the few significant effects of these moderators may indeed be substantive effects supported by theory. For instance, while display hardware did not moderate most relationships, it may indeed moderate the relationship between psychological disorders and VR sickness, and the current observation of this effect was not spurious. We call on future research to continue investigating moderators that were significant for only a few effects, and a particular focus should be placed on the specific instances that they were indeed statistically significant. Similarly, our sample size was quite large, which influences the statistical significance of our results. For this reason, we placed a notable focus on the magnitude of our observed effects rather than their statistical significance alone, and we suggest that future researchers should likewise focus on effect sizes rather than tests of statistical significance.

6 Conclusion

The goal of the current article was to determine which individual differences predict VR sickness, using PIT to develop relevant hypotheses. Our results supported that six individual differences predicted VR sickness: motion sickness susceptibility, gender, relevant real-world experience, technological experience, possessing a neurological disorder, and possessing a phobia. These results did not differ based on the applied technology, suggesting that these effects are resilient across contexts. Individual differences do indeed predict VR sickness, and these results identify a concern that may be dire for the present and future application of VR.

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