Measuring vection: A review and critical evaluation of different methods for quantifying illusory self-motion

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Abstract

The sensation of self-motion in the absence of physical motion, known as *vection*, has been scientifically investigated for several decades. As reliable, objective measures of vection have yet to emerge, researchers have typically employed a variety of subjective methods to quantify the phenomenon of vection. These measures can be broadly categorized into quantitative (e.g., intensity rating scales, magnitude estimation), chronometrical (e.g., onset time/latency, duration), or indirect (e.g., distance travelled) measures. The present review provides an overview and critical evaluation of the most utilized vection measures to date and assesses their respective merit. Furthermore, recommendations for the selection of the most appropriate vection measures will be provided to assist with the process of vection research and to help improving the comparability of research findings across different vection studies.

Translational Abstract

Stationary subjects can experience the sensation of self-motion when sensory inputs convey motion information. This perceptual phenomenon is very robust and is commonly referred to as *vection*. Vection has been investigated for several decades; however, researchers have used a wide variety of approaches to measure vection. When planning an empirical study, this variety of vection measures may cause confusion and limits the comparability of results across studies in general. However, if carefully chosen, these measures allow for evaluating different aspects of the complex phenomenon at hand. In this review article, we present the measurement techniques that have been most used to date and discuss their benefits and limitations. Lastly, we provide recommendations for researchers on the selection of measures for future studies.

Keywords: Self-motion, Measurement, Binary Choice, Two-Alternative Forced Choice, Magnitude Estimation, Rating Scales, Distance Travelled, Chronometric

1. Introduction

The subjective experience of self-motion in the absence of actual, physical motion is commonly termed *vection*. Vection is often exemplified by means of the “train illusion”: This illusion has been described to occur when a person is seated in a stationary train and another stationary train adjacent to the person starts moving. Subsequently, the person in the stationary train feels as if they are moving in the opposite direction of the adjacent train and perceive the adjacent train to be stationary (James, 1890). The first empirical documentation of the occurrence of vection due to visual stimulation goes back to work by Mach (1875). In one of his experiments (i.e., ‘*Versuch 1*’, p. 85-86), Mach described a rotating drum with equidistant vertical stripes (i.e., an *optokinetic drum*) that caused the observer to perceive illusory self-movement and the drum as stationary. Mach concluded that he felt a sensation of movement [“*Ich kann mich wenigstens eines Bewegungsgefühl nicht erwehren*” (p. 86), translated from original German text]. The first appearance of the actual term “*vection*” in the scientific literature can be traced back to work by Fischer and Wodak (1924), although Fischer and Kornmüller (1930a) deferred in their work that the term vection (i.e., ‘*Vektionen*’, p. 447), derived from the Latin verb ‘vehere’[1], was first coined by Tschermak in the early 1920s[2].

1.1. The functional relevance of vection

Despite the long-lasting history of vection, research in this domain has recently gained more traction and attention. A literature search including the term “*vection*” (e.g., title, abstract, keywords) via different search engines (i.e., Scopus, Web of Science; January 10th, 2022) revealed a total of 896 articles published in this domain with a constant increase in vection-related research over the past years. The scientific scrutiny on vection is of importance for several reasons. Firstly, understanding how (illusory) self-motion perception is processed by our sensory systems contributes to our knowledge of how humans perform functionally significant tasks in daily life. Palmisano et al. (2015)

[1] *Vehere* means “*to ride*”; “*vectus est*” translates to “*rode*”.

[2] In one of the works by Fischer and Kornmüller (1930b), a reference is presented to a 1928 article by Tschermak crediting him for the word “*Vektion*” but we were unable to source this article. The reference in question is “A. Tschermak, Med. Klinik, *22*, 770, 1928”, however, volume *24* instead of *22* has also been cited in other works.

suggested that vection could be used to infer and control our actual self-motion, which is of importance when we navigate and spatially orientate ourselves. This functional role of vection is indicative from the research performed by Riecke et al. (2015), who showed that vection facilitates perspective switching, which is utilized in spatial orientation. Secondly, since vection may also tap into processing of actual self-motion, it allows researchers to investigate these self-motion processes when physical self-motion is not possible, for example when using complex neurophysiological imaging techniques such as fMRI (e.g., Kirollos et al., 2017; Kovács et al., 2008). Thirdly, understanding how motion perception occurs can be used to enhance the fidelity of Virtual Reality (VR) applications such as motion simulators (Hettinger et al., 2014). Previous research has shown that vection and presence (i.e., the feeling of “being there”, Heeter, 1992) are positively correlated (Riecke et al., 2005), suggesting that vection is a desired sensation for VR applications. Lastly, vection has been associated with visually-induced motion sickness (VIMS), a sensation similar to traditional motion sickness (Cha et al., 2021; Keshavarz & Golding, 2022). The relationship between vection and VIMS is rather complex (see Keshavarz et al., 2015b, for an overview) and mixed findings have been reported in the past (Kuiper et al., 2019; Nooij et al., 2017; Palmisano et al., 2007), highlighting the need for further research to better understand the relationship between vection and VIMS.

1.2. Current challenges in vection research

Several conceptual and methodological concerns pervade the current vection literature. Firstly, there appears to be an inconsistency with regards to the definition of vection. Palmisano et al. (2015) screened 100 studies on how vection was defined and found that most studies described vection as a visually-induced self-motion illusion. However, vection can be elicited through non-visual sensory modalities (see Hettinger et al., 2014, for an overview), including auditory (e.g., Väljamäe et al., 2005), biomechanical (e.g., Riecke et al., 2011), or tactile (e.g., Murovec et al., 2021) stimulation, making vection a rather multisensory phenomenon. There is a growing body of evidence that vection can be enhanced when several, redundant sensory cues are simultaneously presented (e.g., Murovec et al., 2021; Riecke et al., 2011; Soave et al., 2020). Secondly, there is no consistency with regards to how vection is exemplified to participants in laboratory research studies. Vection is often verbally explained using the train illusion analogy (e.g., D'Amour et al., 2017; Ouarti et al., 2014; Stróżak et al., 2016, 2019; Tinga et al., 2018; Weech et al., 2020; Wright et al., 2006), but Soave et al. (2020) noted that this explanation did not appropriately reflect their participants' experience of vection, which may alter the participants' responses to the vection-inducing stimulation. Using practice trials to familiarize participants with vection is routinely applied, but there is no consistency with regards to the type of practice trial used (e.g., laboratory setting, stimulus).

Lastly, several researchers have pointed out the necessity for identifying reliable and objective measures to quantify vection (e.g., Keshavarz et al., 2015a; Palmisano et al., 2015; Weech et al., 2020). Promising approaches, including the use of electroencephalography (e.g., Berti et al., 2019; see Keshavarz et al., 2015a for a review) or postural measures (Weech et al., 2020), have been introduced recently; however, as these objective measures are still in their infancy and are not accessible to the broader research community, the vast majority of vection studies rely on subjective measures. In this regard, Väljamäe (2009) pointed out that vection research lacks a single and robust measure, and more than a decade later, this issue is still persistent in literature; Berti and Keshavarz (2020) as well as Kooijman et al. (2022) highlighted the variability in the use of vection measures in the context of neurophysiological and tactile-mediated vection studies, respectively. This variability in vection measures does not only make it increasingly difficult to interpret and compare results across vection studies, it makes it also challenging to understand the benefits and limitations of these measures and to choose the ones that are most appropriate for a respective research study.

1.3. The present review

The goals of the present review are to (1) provide a general overview of the most common subjective measures used in vection research, (2) assess the merit of each measure, and (3) provide recommendations on their use for future vection research. Note that the aim of the present paper is not to offer an exhaustive overview of the vection literature per se; for this, we refer the reader to existing reviews for further discussions of vection and related factors (e.g., Berti & Keshavarz, 2020; Hettinger et al., 2014; Kooijman et al., 2022; Palmisano et al., 2015; Väljamäe, 2009). Also, we will solely focus on subjective measures and will not discuss the role of (neuro)physiological measures such as electroencephalography (Keshavarz & Berti, 2014; McAssey et al., 2020; Palmisano et al., 2016a), body sway (Mursic et al., 2017; Tanahashi et al., 2007), or fMRI (Kleinschmidt et al., 2002; Kovács et al., 2008), as these measures are not yet well-established and require further research.

2. Measuring Vection

A variety of techniques to subjectively quantify the sensation of vection can be found in the literature. These methods can be broadly separated into *quantitative responses*, *chronometric measures,* and *indirect measures* (see Table 1). Quantitative responses typically focus on the presence of vection and the assessment of its intensity[3] or convincingness[4]. Common methods include binary choice (e.g., Kleinschmidt et al., 2002; Kovács et al., 2008), Two-Alternative Forced Choice (2AFC, e.g., Farkhatdinov et al., 2013; Ouarti et al., 2014), magnitude estimation (e.g., Bubka et al., 2008; Kirollos et al., 2017; Palmisano & Kim, 2009; Seno et al., 2013), and subjective rating scales such as Likert or Visual Analogue scales (e.g., Arnoldussen et al., 2013; Berti et al., 2019; Hoppes et al., 2018; Pitzalis et al., 2013; Riecke et al., 2006). Chronometric measures, such as vection onset time/latency (e.g., Ouarti et al., 2014; Seya et al., 2015; Väljamäe et al., 2008), vection duration (e.g., Palmisano & Kim, 2009; Seno et al., 2018), and vection build-up time (Riecke et al., 2005c; Riecke, Väljamäe, & Schulte-Pelkum, 2009), have been utilized to record the time-related aspects of vection. In the context of indirect measures, estimations of travelled distance (Fauville et al., 2021; Nilsson et al., 2012; Nordahl et al., 2012; Wright et al., 2006) or pointing tasks (Lepecq et al., 1993; Riecke et al., 2015) have been introduced as potential measures that do not explicitly require a subjective estimation of vection. Each

[3] Vection intensity is sometimes referred to as vection strength. Herein we adhere to vection intensity.
[4] Vection convincingness is sometimes referred to as vection compellingness or vection realism. Herein we adhere to vection convincingness.

of these techniques used to subjectively quantify vection can be employed at a different stage during vection studies, and some techniques capture different components of vection (see Figure 1). As such, each technique has its practical benefit and limitation, which we will discuss in depth in the following sections. A summary of the most common vection measures can be found in Table 1.

2.1. Quantitative Responses

2.1.1. Binary Choice

People make, and are presented with, binary choices on a day-to-day basis. The concept of binary choices and thinking is mostly discussed in the domains of philosophy (Elbow, 1993) or sociology (Germond-Duret, 2016; Wood & Petriglieri, 2005), and due to the common-place use of binary choices it is difficult to trace its historical origin in empirical psychology. In vection research, binary choices are presented to participants by simply asking them whether they experienced vection or not. For example, participants in the studies conducted by Kleinschmidt et al. (2002) and Kovács et al. (2008) were exposed to a vection-inducing visual stimulus inside an MRI scanner and used buttons to indicate whether they perceived self-motion (i.e., vection) or object-motion. Please note that in some studies participants were presented with a vection-eliciting display and had to indicate in which direction they were experiencing vection (e.g., Larsson et al., 2004; Väljamäe et al., 2005). Although this might appear a binary option paradigm, it is in fact a ternary option paradigm since participants are able to indicate the direction of vection (i.e., left, or right) as well as to indicate that they did not experience vection at all.

The binary response format is generally easy for participants to answer and takes less time to complete than a multi-category format (Dolnicar et al., 2011). Additionally, Dolnicar and Leisch (2012) showed that binary response formats were more stable, provided higher concurrent validity, and were completed faster than 7-point multi-category formats. As can be seen in Figure 1, binary responses can be recorded at the earliest stage in the experimental trial. Thus, the binary response format can be used to abort trials upon a response (e.g., see Väljamäe et al., 2005), if one is merely interested in whether participants do or do not experience vection. However, the binary response format has several caveats. For instance, it suffers from the loss of information compared to multi-category formats (Dolnicar, 2003). Dichotomization treats individuals on opposing sides (yes/no) as different, whereas their responses could have been very similar to one another when measured using a continuous scale (Altman & Royston, 2006). Additionally, binary response formats require a large sample size to reach the same statistical power compared to continuous outcome variables (Bhandari et al., 2002). Lastly, a study by Bar-Hillel et al. (2014) showed a bias by participants presented with a binary choice, with the response option presented first being favoured by participants, which questions the validity of presenting participants with a binary choice.

2.1.2. Two-Alternative Forced Choice (2AFC) Task

The origin of the 2AFC task can be traced back to Fechner (1860) who described the method of Just Noticeable Difference, wherein an observer had to indicate which of two presented weights was heavier. In essence, this task presents participants with two alternatives and 'forces' them to make a choice. For example, when the chosen experimental criterium is loudness, participants may have to indicate which of the two presented sounds is the louder one. The 2AFC task is an elementary method to measure the sensitivity of participants to sensory input and is commonly used to determine human perceptual thresholds (e.g., see Camacho et al., 2015; Wang et al., 2016).

The use of the 2AFC method in vection research can be exemplified through the experiments by Farkhatdinov et al. (2013) and Ouarti et al. (2014). Participants in the experiment by Farkhatdinov et al. (2013) were exposed to a sequence of two visual-vibrotactile stimuli. The speed of the visual stimulus was constant over all trials, whereas the intensity and frequency of the vibrotactile stimulation were different between the pairs. Participants then indicated which of the two stimuli elicited stronger vection. Similarly, Ouarti et al. (2014) presented participants with a visual scene showing a cart moving through a tunnel while haptic feedback was provided by asking participants to hold onto a handle. The handle moved proportional to the acceleration of the virtual cart. Following the 2AFC paradigm, participants were presented with two subsequent trials with unique combinations of visual and haptic feedback and indicated which trial elicited stronger vection.

The practical benefit of employing a 2AFC task is that it is easy to understand, simple for participants to perform, and is typically not prone to response biases (Peters et al., 2016). However, similar to binary measures, the dichotomization of outcomes comes at a cost of the loss of information and requires a large sample size or many repetitions. Additionally, data of 2AFC tasks are often interpreted against a pre-determined chance level to identify whether participants' responses were due to chance (i.e., 50%) or due to an effect of the stimulus. Pollet and Little (2017) noted that increasing the number of repetitions/participants produced narrower confidence intervals; however, they still advise testing against a higher chance level than 50% to avoid false positives, even with a sample size as large as 120 with two trial repetitions.

In the context of vection, the most apparent limitation of a 2AFC paradigm is that there is no option for participants to disclose that they did not perceive vection at all. That is, participants are forced to choose the stimulus that generated stronger vection, even if none of the two sequentially presented stimuli elicited vection at all. Thus, there is a risk that participants base their decision on simple heuristics, such as visual velocity or vibrational intensity, instead of the actual sensation of vection. To counteract this, adding a "no" option can be considered (Dhar & Simonson, 2003). Figure 1 shows that 2AFC paradigms are mostly employed at the end stage of a trial. As such, this method is prone to memory-related artefacts; upon presentation of the standard stimulus, participants have to retain the vection information of the standard stimulus during the presentation of the subsequent stimulus, evaluate their vection during the second stimulus, and compare the vection experienced during the standard to the vection experienced during the subsequent stimulus. As such, this method can be cognitively complex and affect participants' performance in accurately reporting on their vection experience. Lastly, as 2AFC paradigms involve the sequential presentation of two stimuli, multiple trials/repetitions are necessary and thus stimulus durations are often kept relatively short. For example, in the study by Farkhatdinov et al. (2013), 36 pairs of stimuli were presented with each stimulus lasting 10 seconds whereas Ouarti et al. (2014) presented 24 pairs of stimuli each having a duration of 25 seconds. However, vection typically takes up to 10 seconds to occur (Berthoz et al., 1975; Palmisano & Riecke, 2018), and thus vection-inducing stimuli are often of longer duration. However, in return longer stimulus durations can be problematic by increasing the risk of memory-related artefacts.

2.1.3. Magnitude Estimation

The paradigm of magnitude estimation (ME) was introduced by Stevens (1956, 1957) in the context of psychophysics and has been used to obtain judgements from participants on the perceived intensity of a certain stimulus with respect to a pre-determined standard stimulus. That is, participants are first presented with a standard stimulus, such as a sound, to which an arbitrary number, such as *50* (i.e., the modulus), is ascribed. When presented with subsequent stimuli, participants must rate the perceived intensity of these subsequent stimuli with respect to the standard stimulus. For example, if a subsequent sound is twice as loud as the standard, participants should assign the number 100 to this sound. According to Stevens, this procedure allows to identify a power law that describes the relationship between the physical increase of a stimulus and the perceived change in stimulus intensity.

The implementation of ME in vection research can be exemplified through a study by Berthoz et al. (1975), where participants were shown a visual stimulus moving at 1 $^{m}/_{s}$ and were instructed that vection experienced during this stimulus should be rated as 100%; this stimulus was considered the standard. To explain the procedure of ME to the participants, the authors then presented a subsequent stimulus moving at a velocity of 0.5 $^{m}/_{s}$ and participants were instructed that vection experienced during this stimulus should be rated as 50%. During the following experimental trials, participants used a lever to indicate the magnitude of their vection experience for each trial with respect to the standard. In another study by Kirollos and Herdman (2021), participants viewed a pattern of vertical stripes rotating around the yaw axis through a Head-Mounted Display. At the start of the experiment, participants were exposed to a visual scene that consisted of vertical stripes rotating clockwise and counterclockwise for 20s each. A value of '50' in terms of vection intensity was ascribed to this stimulus (i.e., the standard stimulus), and participants rated subsequent stimuli on a

0 to 100 scale with reference to this standard. Similarly, Palmisano et al. (2016b) presented participants with a standard stimulus at the start of each block of experimental trials and instructed participants that if they felt they were moving during the standard stimulus it corresponded to a value of 5. In subsequent trials, participants rated the vection intensity after viewing each display by changing the size of a bar chart that had a range between 0 and 10.

The primary benefit of ME is that it provides information on how changes in the physical property of a stimulus (e.g., speed) influence participants' experience of vection (e.g., intensity). Furthermore, ME provides researchers with ratios that have a greater sensitivity to measuring small differences compared to categorical scales (Grant et al., 1990), although anchoring might be an issue in this regard (see, Furnham & Boo, 2011, for a review on anchoring). For example, the presence of an anchor, whether physical or numerical, appears to influence participants' ability to estimate the length of a line (LeBoeuf & Shafir, 2006). In relation to vection research, ME suffers from a similar limitation as the 2AFC paradigm and is prone to memory-related artefacts; participants must retain their vection experience during the standard stimulus and compare it to the subsequent stimulus, which can be cognitively cumbersome. Another limitation of ME is that the degree to which participants experience vection during the presentation of the standard stimulus may differ inter-individually, and thus the ratio between the standard and the subsequent ratings may also differ between participants. For instance, participants are typically asked to assign a certain number to a vection-inducing standard stimulus (Palmisano & Kim, 2009; Weech et al., 2020), although the standard stimulus may in fact induce strong vection in some participants and no vection in others. Thus, the standard stimulus cannot be considered a robust standard that is equal across all participants, unlike physical units such as weight, loudness, or length. As a result, ME can only inform about *changes* in vection ratings, but does not allow to draw any conclusions on the absolute intensity of an individual's vection experience. Additionally, there is a large variability in how ME is applied and therefore cross-comparability of research findings across studies is difficult (Miller et al., 2015). Similarly, the characteristics of the standard and the subsequent stimuli varies between studies, further complicating the comparability of research findings.

2.1.4. Rating Scales

One of the earliest accounts on the use of a rating scale can be found in the second century when the Greek physician Galen developed a hot-cold scale (McReynolds & Ludwig, 1987). In the context of psychology, Thomasius was apparently the first to have implemented rating scales for the assessment of personality factors in 1692 (according to McReynolds & Ludwig, 1984). In general, rating scales contain a closed-end question to which participants can respond via categorical or numerical options. For example, the classic rating scale developed by Likert typically consists of five response levels, ranging from “strongly approve” to “strongly disapprove” with a neutral “undecided” mid-point (Likert, 1932), with seven and nine level variants also being common (e.g., see Taherdoost, 2019, for a review). These response levels can be post-hoc converted into numerical values that enable quantitative statistical analysis. In contrast to Likert scales, numerical rating scales do not assign a positive/negative description to each response levels. Numerical rating scales were first introduced in the context of pain research, often encompassing a scale ranging from 0-10 or 0-100 with anchors describing the start and endpoint (e.g., Downie et al., 1978; Farrar et al., 2001). A similar approach is given in Visual Analog Scales (VAS), originally developed by Hayes and Patterson[5] in 1921, that typically encompass a straight line with anchors at each end describing the extremes of the rated statement. Participants place a single mark onto that line to indicate their rating on the VAS (Marsh-Richard et al., 2009).

In vection research, participants are mostly instructed to utilize numerical rating scales to either 1) rate the ‘intensity’ of their vection sensation, 2) the ‘convincingness’ of their vection sensation, or 3) both. The measurement of vection intensity can be exemplified using the study by D’Amour et al. (2021), where participants viewed alternating black-and-white horizontal bars inducing

[5] Hayes and Patterson termed this the “graphic rating method” (Hayes & Patterson, 1921).

circular vection and were asked to rate vection intensity (“*How strong was the sensation of vection*?”) on a scale ranging from 0 (*no vection*) to 10 (*very strong vection*). Similarly, Kitazaki et al. (2019) measured vection intensity using a VAS scale (“*I felt that my whole body was moving forward*”) in participants who were presented with first-person perspective recordings of someone walking. Riecke et al. (2011) exposed participants to vection-inducing auditory cues while they were performing side-stepping motions on a circular treadmill and asked participants to verbally indicate vection intensity (“*How intense was the sensation of self-motion on a scale between 0-100%?”).*

An example for vection convincingness measures can be found in a study by Lind et al. (2016), where participants laid on an actuated wooden platform and were exposed to a visual scene through a Head-Mounted Display that suggested they were sandboarding down a dune. After each trial, participants completed a series of questions, one of which asked participants to rate the convincingness of the sensation of movement using a 0 to 100 scale. In another study, Riecke et al. (2006) presented participants with a rotating 360-degree images of a market environment which were scrambled to various degrees. After trial completion, participants used a joystick to rate the convincingness of vection on scale ranging from 0% (“*no perceived motion at all*”) to 100% (“*very convincing sense of vection*”).

The main benefit of using rating scales is that they allow to easily capture complex human behaviour (Parker et al., 2013) or multiple health states at the same time (Bleichrodt & Johannesson, 1997); by providing participants with multiple statements to rate, researchers can identify and disentangle different behaviours or health states which might co-occur. As such, rating scales offer more variability in response options compared to, for example, binary choice options. Another benefit of rating scales is that they can be employed either during the trial or directly upon trial completion (see Figure 1), which decreases the chance of memory-related artefacts to occur. Furthermore, rating scales are generally easy to implement by researchers and easy to understand and to use by participants. However, some caveats exist for the use of rating scales. Parker et al. (2013) investigated the reliability of dichotomous and multicategory scales by deriving six different gradations (i.e., 2, 3, 5, 7, 10, and 15 item points) from a quasi-continuous dataset. Their results showed that the performance of scale reliability indices (e.g., Pearson's *r*, Cramer's *V*) behaved differently for each gradation and appeared to be scale dependent. Moreover, reliability indices did not remain constant when higher gradations were collapsed into fewer. As such, there is limited comparability between studies using scales with different gradients. Furthermore, rating scales are vulnerable to cross-cultural response bias (Fischer, 2004) and cultural response tendencies. For example, a study by Tellis and Chandrasekaran (2010) showed that the response tendencies of more than 5500 survey respondents from 15 different countries differed substantially. Lastly, Likert scales are inherently ordinal and the general assumption that the distribution between each item point is equal (i.e., the assumption that on a 0 to 10 scale the difference between 2 and 3 is equal to difference between 7 and 8) is erroneous, and it is therefore incorrect to deduce means and standard deviations from these rating scales (Edmondson, 2005).

2.2. Chronometric Measures

Chronometric measures used in vection research find their origin in mental chronometry often applied in psychological research. Chronometric measures are used to record the time-related aspects (i.e., reaction times, duration) of behavioural responses. Chronometry has a long history with the first human chronometric measures performed by Helmholtz in the mid-1800s on neural conduction rates (see Meyer et al., 1988). However, the first documentation of an experiment with a reaction time measurement in cognitive psychology was done by De Jaager in 1865 (De Jaager, 1865). Due to technological advancements, contemporary researchers have the option to record a variety of chronometric measures to quantify participants' processing speed or other performance-related measures with relative ease. The use of chronometric measures is widespread across various (sub)domains of psychology and engineering. The most common chronometric measures in vection research are described in the following sections.

2.2.1. Vection Latency/Vection Onset Time

In essence, vection latency (VL), also referred to as vection onset time, can be considered a reaction time measurement as participants verbally (Keshavarz et al., 2017; Väljamäe et al., 2008) or mechanically (e.g., button press: Ouarti et al., 2014; Palmisano & Chan, 2004; joystick deflection: Riecke et al., 2005a; Seya et al., 2015) indicate the moment when they start to experience vection. Vection latency is computed by taking the difference between the moment a trial starts[6] and the moment participants indicate they first experience vection, as shown in Eqn.1. Presumably, the first account on the use of a VL measurement in vection research can be found in the study by Brandt et al. (1973). Participants in this study sat on a chair in an optokinetic drum, which rotated around them, and used a stopwatch to record the onset and offset of circular vection. In another study, Berthoz et al. (1975) derived VL from the position of a lever which participants used to quantify the magnitude of the vection experience: VL was derived from the moment the lever passed through a pre-defined threshold. Lastly, seated participants in a study by McAssey et al. (2020) viewed the projection of a rotating cloud of points on a dome-shaped surface and indicated the moment they started and stopped experiencing vection by pushing a button.

$$VL = t_{vection,onset} - t_{trial,start} \quad (1)$$

The primary benefit of using VL is that it is easy to understand and to indicate by participants. Furthermore, it is easy to implement by researchers, either as a verbal measure or by letting participants press a button. Figure 1 shows that VL can be measured at the early stages of a trial and can function as a substitute or corroborator of the binary response measure. Furthermore, VL provides researchers with time-related aspects of vection that cannot be obtained by measures previously described. Recording VL allows to clearly distinguish non-vection segments from vection segments. The segmentation is relevant, for instance, in (neuro)physiological studies that aim to compare (neuro)physiological responses during vection and non-vection episodes, which allows one to clearly

[6] Please note, researchers might have different definitions of the start of a trial. For example, one might consider the start of the trial the moment when the visual cue first *appears*, whereas another might consider the start of the trial the moment the visual cue first starts *moving*.

identify the point in time during a trial when the perception from object-motion transitioned into self-motion (i.e., vection). Lastly, when complemented with other measures, VL provides researchers multidimensional information on participants' subjective experience of vection. It allows to explore the temporal aspects of vection that typically coincide with vection intensity or convincingness but are yet distinct from them

One of the concerns surrounding the use of VL is that responses are likely to be inflated due to participants' naivety, expectation, or confusion (Palmisano et al., 2015), and the accuracy of VLs can be impacted by the task instructions and definition of vection given by the experimenter. For example, participant may be asked to press the button as soon as they experience the slightest sensation of vection in one study, whereas other studies might instruct participants to press a button once they are certain that they are experiencing vection. This ambiguity in task instruction may hamper the overall comparability of VL responses if they are not clearly stated in the respective publication.

2.2.2. Vection Duration

Vection duration (VD) is a measure reflecting how long participants' vection experience lasted and is expressed in either seconds (Kirollos & Herdman, 2021; Palmisano & Kim, 2009; Weech et al., 2020) or in percentage of total trial duration (D'Amour et al., 2017; Seno et al., 2018). However, it is often not explicitly mentioned how VD is computed and inferences must be made from the procedural descriptions in the manuscripts. For example, Kirollos and Herdman (2021) asked participants to press and hold a button on a controller while they experienced vection, which was used to calculate VD. Palmisano and Kim (2009) as well as Weech et al. (2020) used a similar approach only with different pieces of hardware (e.g., joystick or mouse button press, respectively). As such, VD could be computed by 1) taking the difference between vection onset and the total duration of the trial (Eqn. 2), 2) taking the difference between vection onset and the last vection offset that occurs in a trial (Eqn. 3), 3) taking the sum of differences between segments wherein vection onset and offset occur (Eqn. 4), or 4) by dividing Eqn. 4 by the total duration of the trial (Eqn. 5). The latter approach was used by Seno et al.

(2018) to derive VD and account for varying trial durations. Alternatively, some researchers asked participants to verbally report the duration of vection in percentages post-hoc (D'Amour et al., 2017; Murovec et al., 2021), where 0% indicated that participants experienced no vection at all and 100% indicated that they experienced vection throughout the whole trial.

$$VD_1 = t_{trial,end} - t_{vection,onset} \tag{2}$$

$$VD_2 = t_{vection,offset,last} - t_{vection,onset} \tag{3}$$

$$VD_3 = \sum_{i=1}^{n}\left(t_{vection,offset,i} - t_{vection,onset,i}\right) \tag{4}$$

$$VD_4 = \frac{\sum_{i=1}^{n}\left(t_{vection,offset,i} - t_{vection,onset,i}\right)}{t_{duration,trial}} \tag{5}$$

Similar to VL, the main benefit of recording VD is it is easy to understand and to indicate by participants and to implement by researchers, either as a verbal measure or by letting participants press a button. Akin to VL, VD offers information on time-related aspects of vection that other measures cannot offer. Figure 1 shows that VD can be measured throughout the trial, and it thus provides researchers with the opportunity to clearly identify segments within a single trial where vection was perceived. However, this holds true only when VD is assessed using, for example, a button press, but not with post-hoc verbal assessments. The segmentation of vection trials can be helpful for (neuro)physiological studies, where (neuro)physiological responses can be interpreted based on VDs, allowing to compare stages pre-vection, during vection, and post-vection. Lastly, when VD is accompanied to other measures, the combined measures can provide multidimensional information on participants' subjective experience. For example, prolonged VDs might coincide with reduced VL and increased vection intensity. Indeed, the study by Seno et al. (2017) showed that generally longer VDs correlated to shorter VLs and higher vection intensities. Furthermore, the model developed by the authors, which used VD, VL, and vection magnitude as indices, was able to predict to participants' vection experience to a reasonable degree. Nonetheless, with the potential variability in which VD could be calculated, and the lack of reporting the way VD is calculated, the comparability of research findings is hampered. Moreover, the accuracy of VDs is impacted by the limitations presented for VLs as the computation of VD is dependent on the onset of vection.

2.2.3. Vection Build-up Time

Vection build-up time (VBT) is used as an indication on how long it takes for vection to reach full saturation. VBT is computed by taking the difference between the moment vection first occurs (i.e., VL) and the moment when maximum or saturated vection occurs (Riecke et al., 2005a), as can be seen from Eqn. 6. In studies conducted by Riecke and colleagues (e.g., Riecke et al., 2005a, 2005b, 2005c; Riecke, Väljamäe, & Schulte-Pelkum, 2009), participants pulled a joystick in the direction they experienced circular vection and increased the angle of deflection proportional to the intensity of their vection experience. The point where the joystick reached its maximum angle was defined as fully saturated vection.

$$VBT = t_{vection,\max} - t_{vection,onset} \tag{6}$$

Vection build-up time shares many of the benefits that have been listed for VL and VD. That is, the recording of VBT is quite simple, time-efficient, and easy to understand for participants. In addition, when recorded together with other vection measures, they allow to gain multidimensional information on participants' vection perception. Again, VBT enables (neuro)physiological studies to specifically identify and focus on the segments wherein vection develops, as well as on vection segments that contain fully saturated vection, and compare them with pre- and post-vection segments. However, it is possible that strong and weak vection displays result in, on average, same build-up time (e.g., see Figure 4 in Seya et al., 2015). Similar to VD, the accuracy of VBT is also impacted by the limitations presented for VL as the computation of VBT is dependent on the onset of vection. Additionally, the recording of VBTs requires the use of joysticks or sliders which requires the need for 1) training participants and 2) programming software to collect information on the position of the joystick/slider over time. As such, VBTs lack standardization as joystick deflections and/or slider positions are prone to variability in ratings between participants.

2.3. Indirect Measures

Besides directly enquiring participants about their vection experience, participants' vection experience might also be assessed through indirect measures. Some of these measures offer participants to quantify their vection experience in terms of physical motion properties, such as estimations of the distance travelled (Fauville et al., 2021; Nilsson et al., 2012; Nordahl et al., 2012; Wright et al., 2006) or estimations of self-motion velocity (Riecke, Feuereissen, & Rieser, 2009). Other measures attempt to quantify participants' vection experience in terms of spatial orientation (Lepecq et al., 1993). However, these indirect measures do not directly measure vection in the sense that they attempt to quantify vection intensity, convincingness, or duration, but rather they are being used as an indicator for the perception of vection. Note that accurate performance in some of these indirect measures (e.g., estimation of self-motion velocity) can be achieved based on visual parameters alone (e.g., optic flow) and does not necessitate the ability to experience vection, questioning the validity of such measures for vection research. However, the implementation of indirect measures allows for a more direct investigation of the functional significance of vection (i.e., the effect of self-motion on behavioural adaptation). Nonetheless, we will briefly discuss the employment of two indirect measures which are commonly used in vection research and highlight their individual benefits and limitations.

2.3.1. Pointing

The pointing technique requires participants to point to either a remembered target (Lepecq et al., 1993) or continuously point towards the perceived location of a target (Riecke et al., 2015). Pointing tasks are predominantly performed with participants having their eyes closed (e.g., Riecke et al., 2015; Siegle et al., 2009). Lepecq et al. (1993) hypothesized that if participants experienced vection, their pointing angle would deviate from the actual position of a remembered target prior to the vection experience. To test this, participants performed three different pointing tasks, namely 1) pointing to visually present targets, 2) pointing to the memorized direction of previously presented visual targets, and 3) pointing to the memorized direction of priorly presented visual target after viewing a display aimed to elicit forward vection. The authors found that the pointing error increased when participants pointed to targets in their lateral field of view after being exposed to a vection-inducing display. In a study by Riecke et al. (2015), blindfolded participants were seated in a hammock chair and participants used a joystick to continuously point to the location of the sound of an owl that surrounded them. The authors hypothesized that if participants truly experienced vection, they would change their pointing direction to follow the illusory motion of the auditory cue. Depending on the condition, stereo or mono recordings of the rotating sound field were presented to participants to account for the possibility of external sounds influencing participants perception. No significant differences in the pointing errors were found between conditions in which participants experienced vection and conditions in which participants physically moved.

The primary benefit of pointing measures is their ability to quantify participants' vection experience in form of a physical motion property that does not rely on subjective ratings. These physical motion properties could be related to functional motion processes. For example, the study by Riecke et al. (2015) showed that the experience of vection can influence participants' pointing error and facilitate perspective switches, thereby indicating that vection can affect functional processes. As can be seen from Figure 1, pointing can be employed as a continuous measure, which reduces the possibility of memory-related artefacts during post-hoc judgements and can capture online self-motion processing (Siegle et al., 2009). However, the major limitation of pointing tasks is that the interpretation of the pointing error metric mirroring (potential) changes in vection is difficult. For example, it is not clear whether a larger deviation in pointing angle to a remembered target truly indicates a stronger vection sensation or whether this deviation is a result of stimulus context/characteristics. As such, pointing tasks could be used to compliment more 'conventional' vection measures. Another limitation is that pointing tasks require certain equipment that allow to accurately measure certain body movements, and this equipment might not be easily accessible.

2.3.2. Distance Travelled

Generally, the distance travelled (DT) measure describes how far participants perceive they have moved (or travelled) during an immersive virtual scene. For instance, participants in a study by Nilsson et al. (2012) stood on a platform and were exposed to four different static VR scenes while being subjected to vibrations to their feet eliciting tactile-induced vection. After each trial, participants estimated the distance they had virtually travelled in meters for each of the different VR scenes. The authors used DT in their study as an indication of vection intensity while they also collected verbal vection convincingness ratings. Similarly, Nordahl et al. (2012) visually immersed participants who were standing on a platform into a virtual elevator; again, participants estimated the (vertical) distance they had virtually travelled in meters. In another study, Fauville et al. (2021) showed participants an orange marker located either on the floor or in the water of an actual swimming pool prior to immersing participants in a virtual environment wherein they perceived to be swimming. Upon completion of a swimming trial, participants were asked to indicate how far they had travelled from the orange marker.

The main benefit of DT is that participants can quantify their vection experience through a metric of length (e.g., metres, feet, or yards). However, alike the pointing paradigm, it is currently unclear how DT is to be interpreted in relation to vection. For example, it is unclear how changes in DT reflect actual changes in vection perception. That is, it remains uncertain whether a larger DT indicates a more intense or more convincing vection sensation. For instance, previous research by Bremmer and Lappe (1999) showed that participants can utilize visual information alone to accurately reproduce DT estimations. As such, it is possible that participants rely on visual information to make DT judgements rather than deriving this estimate from their vection experience. Furthermore, Nilsson et al. (2012) argued that the larger DT found in one of their four experimental conditions does not necessarily imply that vection was "*superior to the ones elicited by (…) the other two conditions for that matter,*" (p. 358) as vection convincingness ratings did not differ between conditions. Instead, participants' DT estimation could have been affected by the context of the virtual scene according to the authors. Lastly, the utility of DT is limited to studies on *linear vection* as it cannot be applied in its current form to studies on *circular vection*.

3. Discussion and Recommendations

The summary of the existing measures applied in vection research demonstrates the large heterogeneity in methods to capture vection. It also shows the lack of established methodological procedures that are generally agreed upon in the research community. This raises the question on how this multitude of measures, which are all supposed to capture the same phenomenon, should be evaluated. On the one hand, this variety in vection measures mirrors the complexity of the phenomenon in question: vection is not only a subjective experience but it can also be perceived in very different ways. For example, the same visual input may generate a strong sense of vection that only lasts for a short period of time in one observer, while another observer may experience only a faint sensation of vection that starts very quickly and lasts for a prolonged time. A third observer, in contrast, may experience no vection at all. From this perspective, it seems beneficial for researchers to have a broad variety of measurement tools available to capture the different aspects of vection. However, the potential variance in participants' vection experience also implies that a single measure that could fit all situations does not exist, and that the appropriate measures need to be carefully selected on an individual (i.e., experimental level) basis. This selection requires a thorough consideration of at least two aspects when designing and conducting an experimental study: (a) the general research question and (b) the specific characteristics of vection that best represents the research question. For instance, imaging studies investigating the neurophysiological correlates of vection may only be interested in comparing vection versus non-vection episodes, whereas individual differences in vection duration and/or intensity might not be relevant. In these cases, it seems reasonable to choose a binary (yes/no) response format to accurately differentiate between vection and non-vection episodes. In contrast, studies exploring the influence of cognitive aspects of vection may very well be interested in nuanced differences in the experience of vection, making the choice of vection intensity, duration, and onset measures appropriate. Thus, it seems generally a good idea to apply several different measurement methods when appropriate rather than just one. In contrast, it is not advisable to simply motivate the selection of the applied vection measure on any study that potentially examines a completely different question. But, of course, pragmatic limitations regarding the number of measures that can be applied during an experiment need to be considered as well.

On the other hand, the multitude of measures utilized in vection research impairs the comparability and integration of studies and their findings. It is particularly problematic if individual studies not only use different measures in principle, but if these measures are also used in different fashion. For example, a rating scale used to capture vection intensity can range from 0 to 10, including a “no vection” option. However, this intensity rating scale can also be used as a follow-up question after a participant has indicated having experienced vection. At this point, the scale value "zero" is de-facto redundant and could be technically omitted. This raises the question whether the two scales depict the same measure in both cases and are still comparable or whether participants scale their experience differently in the two cases. However, a direct investigation of the effect of different rating scales on vection measures has yet to emerge. A similar problem exists when using magnitude estimation, albeit more subtly: Even if all studies used the same range (e.g., 0 to 100) and same anchor value (e.g., 50), the actual scaling will strongly depend on the actual stimulus, which is presented to the participants as the “standard”. In other words, the standard might be perceived differently by different participants, limiting the comparability of magnitude estimation ratings in the context of vection research.

Certainly, more standardization when conducting vection research would be desirable; however, research should, of course, not be limited too much, because there may be good reasons for the individual choice of measures and settings. The main issue however is that the reasons behind the choice of the specific measures and settings are rarely communicated in the dissemination of the results. To allow for comparability of studies (or to be able to evaluate the incomparability of individual studies), more transparency is needed: the exact settings used in each measure, but also all details of instruction and (vection-inducing) stimulation should always be reported. Unfortunately, this accuracy is not consistently met (see Berti & Keshavarz, 2020).

As a first step into developing a standardized framework for vection research, more qualitative research should be conducted to understand how participants experience vection and what wording should be used to query and describe their experience. For example, Soave et al. (2021) investigated participants' perspective on the phenomenon of vection and inquired whether the presented terminology matched participants' intuition. The authors discussed that the way in which people think about themselves is generally split between the physical and subjective domain, and accordingly different terminology is more representable to describe perceptions (e.g., self-motion velocity, distance travelled) and sensations (e.g., vection). The results of their online study showed that participants interchanged terms such as "sensation" and "feel" but never substituted them with the term "perception". Similarly, some participants denoted that the term "movement" was related more to the physical self, whereas the term "motion" was more related to the abstract domain. Additionally, the effect of terminology could also extend to which aspect of vection is measured. For example, utilizing a vection intensity measure (e.g., "*How intense was the sensation that you were moving in the space?*", Pitzalis et al., 2013) when presenting participants with combinations of visual, auditory, and tactile cues might not be ideal in this situation; instead, a measure of convincingness (e.g., "*How convinced were you that you were moving in the space?*") might be more appropriate as multisensory stimulations might affect convincingness more than intensity (see discussion Kooijman et al., 2022).

Lastly, it should be kept in mind that a reliable objective measure of vection has not yet been successfully established. Instead, most of the measures summarized here are purely subjective. However, one must also keep in mind that vection is, of course, a purely subjective experience unlike physical movement that can be objectively measured. Based on these considerations, the following recommendations seem appropriate to us for guiding the selection of one or more vection measures for a specific study:

1. As the first step in choosing the appropriate vection measures, it is important to be aware of the different definitions and types of vection, which can be found in the empirical literature (see Palmisano et al., 2015). Based on this, it is important to explicitly set the relevant vection definition for the study. The selected definition may already limit the applicable vection measures and can, for example, assist in defining how chronometric measures are computed.

2. One could consider combining complementary measures (e.g., ratings scales for intensity/convincingness and chronometric measures, such as VD) to capture the different aspects of vection. The multitude of measures would allow for the application of multivariate statistical analysis of the data to test the complex sensation of vection in a more holistic way.

3. Based on the task that participants are expected to perform, a preliminary selection of the type of vection measure could be made. For example, if participants are required to use their hands to control a steering wheel, measures derived from joysticks or button presses might not be a convenient option and one might have to resort to verbal measures. Furthermore, a trade-off needs to be made between experimental demands and memory-related artefacts. Online measures, such as button-presses or joystick inclinations, might increase the experimental demands imposed on the participant at the gain of avoiding memory-related artifacts in a measure. However, if participants are expected to perform multiple tasks during a trial, it might be beneficial to initiate some measurements *after* the trial to reduce experimental demands *during* the trial. For example, one could implement a button press during the trial to gain insight on vection onset and duration, but measure vection intensity and/or convincingness after completing the trial. Additionally, caution should be exerted in the number of measures used; as it is recommended to measure vection, presence, and discomfort (e.g., cybersickness or motion sickness) sequentially (Weech et al., 2019), one must be cautious to not overload the participant with queries on different sensations (e.g., multiple vection measures and detailed questions on sickness symptoms) and states (e.g., the sense of presence).

4. It is highly recommended to offer participants a vection measure that includes the option to indicate that no vection was experienced at all. This can be done either by combining measures or by using a respective rating scale (e.g., 0-10).

5. When detailing the experimental procedure in the manuscript, we recommend refraining from paraphrasing the instructions given to participants to measure their vection and instead report these instructions in verbatim. For example, when using a vection rating scale one might instruct the participant to "*please rate the intensity of your self-motion sensation*" whereas when one utilizes magnitude estimation the instruction might have been "*please rate the intensity of your self-motion sensation with respect to the first stimulus*". Explicitly including these statements in a manuscript helps to clearly understand the used methodology and to interpret the results accordingly.

6. When utilizing rating scales, it is also important to avoid paraphrasing when describing the end points of the scale in the manuscript and denote the *exact* endpoints of the scale and the definition of intermediate response options (if given). For example, if the left and right anchor of the scale were "*No sensation of self-motion*" and "*Very strong self-motion sensation*", one should not detail these anchors in the manuscript as "*no vection*" and "*very strong vection*". Moreover, it should be specified if the scale was ordinal (e.g., Likert) or continuous (e.g., VAS).

7. Be prepared to mitigate setbacks. It is likely participants become overwhelmed by the sensations the vection-inducing sensory stimuli may elicit and, as such, forget to press a button or pull on a joystick. Furthermore, participants may misinterpret task instructions and respond to different aspects of the display (e.g., the velocity component). These challenges could be mitigated by presenting a practice trial, verifying that participants understood the task instructions after the practice trial and possibly reinstructing the participant. It is also important to debrief participants, through which one could uncover *how* participants performed the task and *wha*t they experienced.

4. Conclusions

The goal of the present paper was to review the scientific literature in order to provide the readership with a general overview of the most common measures utilized in vection research. A variety of different methodological approaches were identified and assigned to three categories: quantitative, chronometric, and indirect measures. For each of these measures, we discussed the benefits and limitations and provided recommendations on how to best select and use these measures when conducting empirical vection studies. Ideally, the measure(s) of choice should provide participants the option to disclose they did not experience vection, either by combining different measure types or utilizing a measure with a "null" response option. Furthermore, combining chronometric measures with quantitative response measures is advisable to capture the multidimensional aspect of vection and allow for a multivariate statistical analysis. Further, caution should be exerted not to overload participants with various measures.

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Data Availability Statement

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Table 1.

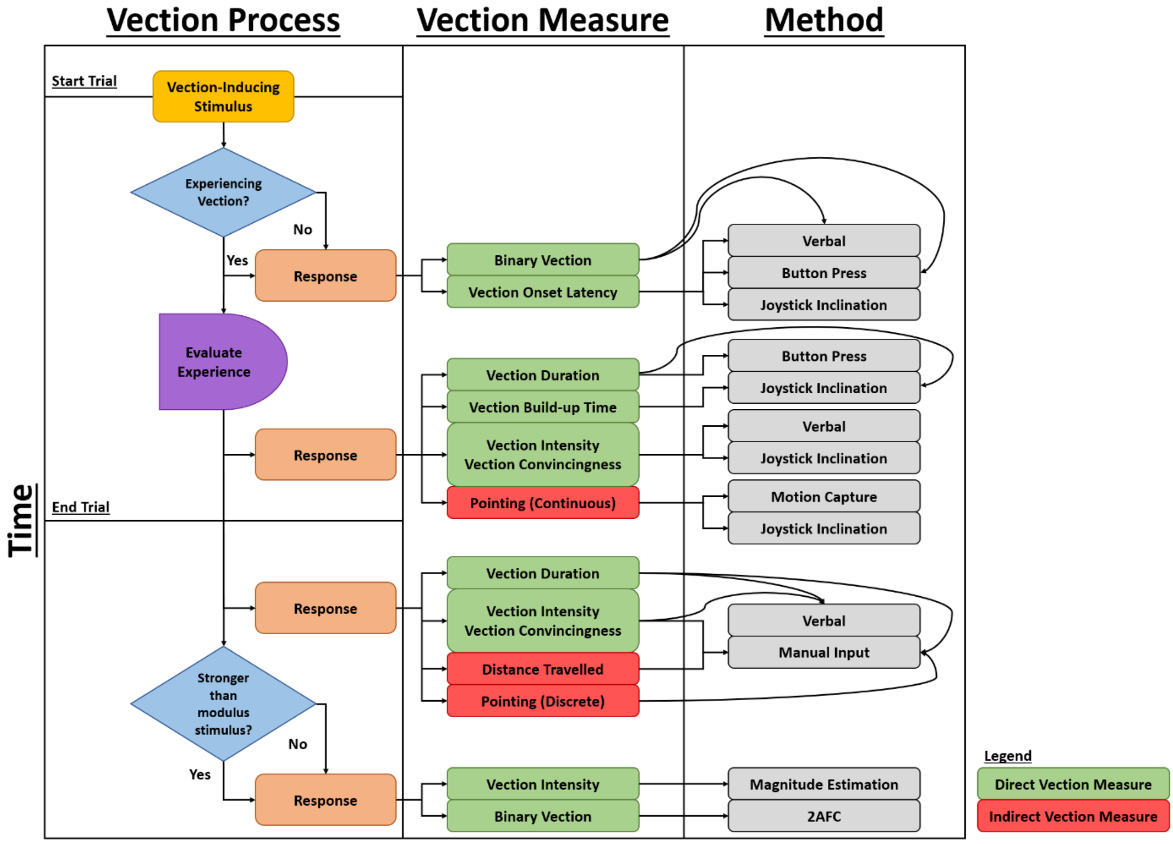
Overview of measures utilized in vection research

Measure	Method	Example in Vection	Benefits	Limitations
Quantitative				
Binary Response	• Verbal • Button press	While experiencing a display, participants indicate verbally or by pressing a button they are experiencing vection.	• Easy to understand by participants. • Allows categorizing trials as vection / no vection.	• Insensitive to quantify small differences (within-subject). • Requires large sample/repetitions.
Two-Alternative Forced Choice	• Verbal • Button press	After experiencing two displays, participants indicate which of the two displays elicited the strongest vection either verbally or by pressing a button (e.g., left or right mouse button).	• Less chance of response bias. • Easy to understand by participants.	• Requires large sample/repetitions.
Magnitude Estimation	• Joystick • Verbal • Writing	Participants experience a standard display to which they ascribe an arbitrary value for their vection experience. Participants view subsequent displays and ascribe to these displays a value relative to the value they ascribed to the standard display either verbally, via digital input or in writing to rate their vection experience.	• Sensitive to quantify small differences. • Able to account for individual differences.	• Between-subject variance in ratios requires data transformation. • Potential anchoring effect. • Limited cross-comparability between studies due to variability in methodology.
Ratings	• Joystick • Verbal • Writing	After experiencing a display, participants rate their vection experience based on a statement. The lower and upper end of the rating scale have a description reflecting the extremes of participants' vection experience.	• Sensitive to quantify small differences • Able to account for individual differences	• Terminology influences participants' responses. • Cultural response bias. • Most scales are ordinal from which common descriptive statistics cannot be derived.
Chronometric				
Vection Latency	• Verbal • Button press • Joystick deflection	While experiencing a display, participants indicate verbally or by pressing a button they are experiencing vection and the experimenter records the moment in time relative to the start of the trial.	• Allows for interpretation of multidimensionality of vection when complemented with other measures. • Provides the option to correlate and interpretate (neuro)physiological measures.	• Potential to be inflated by participants' mental demands.
Vection Duration	• Verbal • Button press	While experiencing a display, participants indicate the time they are experiencing	• Allows for interpretation of multidimensionality of vection	• Potential to be affected by participants' mental demands.

	• Joystick deflection	vection. From this data, the experimenter computes participants' vection duration.	when complemented with other measures. • Provides the option to correlate and interpretate (neuro)physiological measures.	
Vection Build-up Time	• Joystick deflection	While experiencing a display, participants move a joystick to indicate the intensity or convincingness of their vection experience. From the joystick data, the experimenter computes the time between vection onset and maximum vection.	• Allows for interpretation of multidimensionality of vection when complemented with other measures • Provides the option to correlate and interpretate (neuro)physiological measures.	• Potential to be affected by participants' mental demands.
Indirect				
Pointing	• Continuously point at target. • Point to remembered target at end of trial.	Participants either point continuously to a specific target while being subjected to a display or point in the direction of a remembered target after experiencing a display.	• Gain insight of influence vection on (functional) self-motion processes. • Online pointing reduces chance of memory-related artefacts.	• Does not measure *vection* directly. Thus, difficult to interpret.
Distance Travelled	• Verbal • Writing	After experiencing a display, participants either verbally or type in the number of meters they felt they had travelled.	• Gain insight of influence vection on (functional) self-motion processes.	• Does not measure *vection* directly. Thus, difficult to interpret. • Outcome potentially biased by (visual) context.

Figure 1

Vection measures used depending on when participants are probed during a vection experiment.



Note: Measures can either be during the trial or post hoc and can be continuous or discrete.