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Review

Association between spatial neglect and impaired verticality perception after stroke: A systematic review

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ABSTRACT

Background: Although most research on spatial neglect (SN) has focused on spatial perception deficits with regard to the lateral (left-right) axis, deficits of spatial perception with regard to the vertical (up-down) axis, such as disturbances in the perception of verticality (e.g., judgement of vertical orientations), have also been suggested.
Objective: We aimed to systematically analyse reported associations between SN and characteristics of verticality perception while considering the time post-stroke.
Methods: PubMed, Web of Science, Scopus, PubPsych and PsycArticles databases were searched on May 24, 2022 for articles written in English that evaluated the association between SN and verticality perception (i.e., the subjective visual vertical [SVV], subjective postural vertical [SPV] and subjective haptic vertical [SHV]) in adults after stroke. Left and right SN were considered and had to be assessed using standardized methods. Data were manually extracted, and risk of bias was assessed with the Newcastle-Ottawa Scale. The tilt of the line/chair relative to the gravitational vector and its direction, together with uncertainty (i.e., variability across measurements), were evaluated.
Results: Thirteen studies were included (431 participants after stroke); at least 191 participants exhibited SN. Mainly the first 3 to 6 months post-stroke were evaluated. SN was associated with SVV misperception, which resulted in larger SVV tilts (mostly in the contralesional direction) and uncertainty in participants with than without SN. SVV tilt magnitudes ranged from a mean/median of -8.9° to -2.3° in SN participants and from -1.6° to 0.6° in non-SN participants, the latter falling within normative ranges. For SPV and SHV measurements, the magnitude of tilt and the uncertainty were insufficiently assessed or results were inconclusive.
Conclusions: SN was associated with larger SVV tilts and uncertainty, which suggests that SVV misperception is a key feature of SN. This observation highlights the importance of regular SVV assessment in people with SN in clinical practice.
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Introduction

Spatial neglect (SN) is a post-stroke disorder of lateralized spatial cognition, awareness and attention [1]. It is a cognitive disorder that cannot be attributed to sensorimotor or memory impairments [2]. The estimated prevalence of SN after a unilateral stroke is 30%, and SN is more common after right- than left-sided stroke [3]. Classically, SN is considered a disorder of spatial perception with regard to the lateral (left-right) axis. This condition is clinically evident, with SN participants demonstrating decreased ability to report upon contralesional (and in some cases with moderate to severe SN also ipsilesional) stimuli and failing to explore the contralesional hemispace with their eyes and limbs [4,5]. Although most research on SN has focused on spatial perception deficits with regard to this lateral axis, deficits of spatial perception with regard to the vertical (up-down) axis, such as disturbances in the perception of verticality (e.g., judgement of vertical orientations), have also been suggested [4–6].

Verticality perception is built up around internal models of verticality, established by the convergence of multisensory graviceptive

Abbreviations: SN, spatial neglect; SHV, subjective haptic vertical; SVV, subjective visual vertical; SPV, subjective postural vertical

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information (i.e., somatosensory, visual, vestibular) [7]. The more precise and congruent this information is across sources, the more accurate the internal model of verticality [7]. Clinically, this internal model of verticality can be estimated by evaluating the perception of verticality, based on visual information (subjective visual vertical [SVV]), postural information (subjective postural vertical [SPV]) or haptic information (subjective haptic vertical [SHV]). An accurate perception of verticality is considered essential for postural control and therefore is crucial for performing various functional activities such as standing and walking [8–10].

After a stroke, afferent information congruency or its processing can be impaired, thus hampering the spatial representation of the gravitational vector. Previous literature has already proposed a link between SN and verticality misperception [4,6,11, 12], which resulted in 3 interpretations [4]. The first interpretation states that a stroke may affect 2 distinct but neighboring neural networks, one coding spatial information for the lateral axis and the other for the vertical axis [13]. In the second interpretation, a stroke would affect certain networks that process 3-D spatial information, inducing SN and verticality misperception simultaneously [5]. The last interpretation implies a form of SN bearing on graviception [6]. It involves verticality construction from vestibular and somesthetic input and suggests the existence of a "graviceptive neglect". In this case, gravitational information would be non-symmetrically processed, thus resulting in a biased perception of verticality [4,6,11,12].

Although the association of SN with verticality misperception seems plausible, how this association is represented remains unclear [4,14]. This systematic review aimed to analyse the literature on reported associations between SN and characteristics of SVV, SPV and SHV. Because verticality misperception may differ according to the time post-stroke [15], we considered the time post-stroke when analysing the results.

Methods

Protocol and registration

The protocol of this systematic review was registered at PROSPERO (CRD42019127616) and the review adheres to the guidelines of Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) [16] and Synthesis Without Meta-Analysis (SWiM) [17] guidelines (See Supplementary E-files: PRISMA and SWiM guidelines).

Definitions

Definitions concerning the criteria related to SN, verticality perception, time post-stroke, and potential comorbidities were used to decrease the potential for ambiguity in article selection. SN was defined as a disorder of lateralized spatial cognition, awareness and attention [1], causing decreased ability to report upon contralesional (and sometimes ipsilesional) stimuli not attributable to sensorimotor or memory impairments [18]. The association of SN with verticality perception is evaluated across the post-stroke time phases. Four phases are described: acute phase (1–7 days), early subacute phase (1 week to 3 months), late subacute phase (3–6 months), and chronic phase (>6 months) [19].

Clinically, the internal model of verticality can be estimated by evaluating the perception of verticality, measured with 3 modalities: SVV, SPV and SHV. SVV, SPV and SHV concern the subjective perception of the visual, postural and haptic vertical, respectively, as compared with the true vertical (i.e., gravitational vector). SVV relies on visuo-vestibular information, SPV on proprioceptive, tactile and visceral-graviceptive information and SHV on tactile information [20].

The magnitude of tilt of the line/object/tilt chair (V) relative to the true vertical is described in relative (i.e., constant errors) and absolute values (i.e., unsigned errors). The constant errors represent the magnitude of tilt of the object/tilt chair with respect to the true vertical while considering the direction of tilt. Negative values indicate a counterclockwise tilt of the subjective vertical and positive values a clockwise tilt. However, for this systematic review, the direction of tilt is described in relation to the stroke side and therefore can be contralesional (in a right-sided lesion, this implies a leftward or counterclockwise tilt) or ipsilesional (in a right-sided lesion, this implies a rightward or clockwise tilt). Reported normative values for SVV (-2.5° to 2.5°) [14,21], SPV (mean 0.12°, standard deviation 1.49°) [14,21] and SHV (-4.5° to 4.5°) [14] were used to compare reported tilts. A tilt was considered "biased" if it falls outside of these reported normative values. Unsigned errors represent the magnitude of tilt with respect to the true vertical, regardless of the direction of tilt.

Uncertainty (U) of the measurements relates to the intra-individual variability of the tilts across the measurements. This situation reflects the robustness of the internal reference of verticality [21]. The higher the uncertainty, the more the magnitude and/or direction of the tilt of the subjective vertical differs between trials, which indicates that the individual is uncertain about the vertical position between trials.

We also considered the co-existing influence of lateropulsion with SN to the verticality perception measurements, when investigated by the included studies. Lateropulsion refers to a lateral push at the origin of a lateral body tilt. This push can be performed by the non-hemiplegic side generating a body tilt toward the opposite side [22].

Search strategy and study selection

A systematic literature search was conducted on May 24, 2022 in PubMed, Web of Science, Scopus, PubPsych and PsycArticles databases. Search queries consisted of the following free-text terms and medical subject headings: "SN", "stroke" and "perception of verticality" and their synonyms (See Supplementary E-Files: Search strategies). No restrictions or filters were added. Studies were included if they 1) investigated adults after stroke, with no restrictions on lesion characteristics; 2) evaluated an association between SN and the perception of verticality by comparing participants with and without SN or by evaluating this association using correlation or regression analyses (the contribution of SN to the outcome had to be evaluated); 3) evaluated SN using standardized assessment methods; 4) evaluated SVV, SPV and/or SHV; and 5) were written in English. For intervention studies, only baseline characteristics were considered. We excluded studies that 1) had no full-text article available; 2) were reported as case reports, meta-analyses, reviews or abstracts; 3) evaluated combined modalities (e.g., visual and postural/haptic) such as the SPV-eyes open and SHV-eyes open; and 4) solely and specifically included participants with lateropulsion, even if they also evaluated the perception of verticality between those with and without SN. Studies of participants with lateropulsion were excluded because of the complexity of the disorder and because a recent systematic review showed an association of lateropulsion with verticality misperception in all modalities [23].

To avoid multiple publication bias, potential series overlap between studies was evaluated based on geographic setting and recruitment period. Corresponding authors of relevant studies were contacted if potential overlap between studies was unclear. If overlap in series existed between studies evaluating the same outcome (i.e., SVV), the most relevant study was chosen based on a predefined list of priorities consisting of 1) evaluated outcome (both SVV and uncertainty, instead of only tilt or uncertainty), 2) sample size, 3) risk of bias and 4) choice of SN tests (the more validated tests used, the better).

Four reviewers (EE, DA, AL, JVB) independently screened titles, abstracts and full texts by using a double-blinded approach. During full-text screening, reference lists of included studies were screened

for secondary literature. Disagreements between reviewers were resolved by discussion.

Quality assessment

Three reviewers (DA, AL, JVB) independently assessed the risk of bias of the included studies by using the Newcastle-Ottawa Scale. Disagreements were resolved by discussion. According to the study design, the checklist for longitudinal cohort or cross–sectional studies was used. The items were adapted to fit the research questions (See Supplementary E-file: Newcastle-Ottawa Scale adapted for cross-sectional studies). This scale assesses the risk of bias using a star rating system, judging 3 categories: selection, comparability and outcome. A star was given if a predefined criterion was met, thus suggesting low risk of bias for that criterion. In total, 9 stars could be obtained for longitudinal studies and 10 for cross-sectional studies. Cut-off values as described by McPheeters et al. [24] were used for interpretation (score ≥7 was considered good, 5 or 6 moderate and <5 poor). For intervention studies, the checklist for cross-sectional studies was used because only the pre-intervention characteristics of participants were investigated.

Data extraction and analyses

The association between SN and verticality misperception was evaluated by analysing reported (mean/median) differences between groups (SN and non-SN participants) and/or by evaluating reported associations (e.g., correlations, regressions). Two researchers (EE, CvdW) independently extracted the following data from each included study: authors, year, study design, participant groups, age, time post-stroke of initial and final assessment (if applicable), and SN assessment tools used. Moreover, measurement methods and study results regarding the association of SN with verticality perception were collected. Disagreements were resolved by discussion.

Results

Study selection

In total, 1420 unique articles were retrieved. After screening on the title and abstract, 34 studies were considered; 13 were included after full-text screening (Fig. 1).

Participants and descriptive data

Eleven studies were cross-sectional [11,25-34], and 2 were longitudinal prospective studies [8,15]. In total, 431 stroke participants were studied (327 right-sided, 82 left-sided, 22 unknown) (Table 1). At least 191 showed SN and at least 205 did not. Of the 35 leftover participants, articles did not report whether they did or did not show SN. The reported mean/median age of the participants ranged from 52 to 71.8 years. Eleven studies assessed visuo-spatial neglect [8,11,25,27-34], 9 with conventional paper-and-pencil tests only [8,11,25,27,29,30,32-34] and 2 with the Behavioral Inattention Test

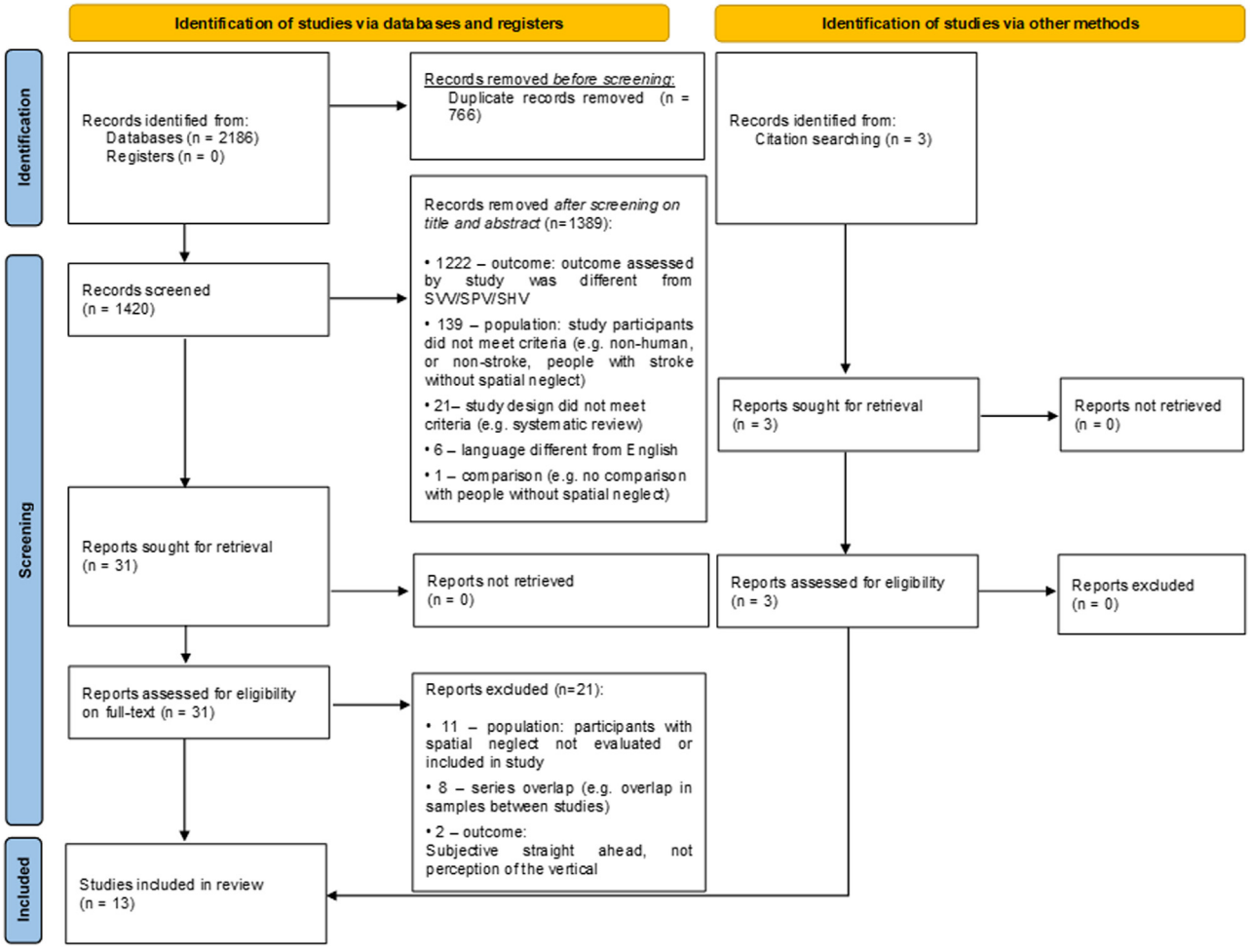

Fig. 1. Flow of articles/studies in the review.

Table 1
Sample characteristics.

Author	De-sign	Participant groups according to lesion side (N)	Age in years (SD/IQD/ range)	Time phase post-stroke of verticality measurements	Spatial neglect test	Spatial neglect diagnosis criteria
Baier et al. (2012) [25]	CS	**RBD (n=32):** SN+ (n=12), SN- (n=20); **LBD (n=22)**: SN+ (n=2), SN- (n=20)	**RBD+LBD:** 61.0 (SD 18)	*Early subacute* ***RBD:*** *4.5 (SD 2.1) days* ***LBD:*** *4.9 (SD 5.2) days*	Bell's test (Center of Cancellation)	NM
Barra et al. (2009) [26]	CS	**RBD (n=13), LBD (n=9)**	*57.14 (SD 13.7)*	Early to late subacute phase ***RBD:*** *12.3 (SD 6.9) weeks* ***LBD:*** *14.4 (SD 8.0) weeks*	Bell's test, LBT, behavioral scale	NM
Bonan et al. (2006) [15]	C: pro	**RBD (n=13)**: SN+ (n=11), SN- (n=2); **LBD (n=17)**: SN+ (n=2), SN- (n=15)	**RBD**: 55 (IQD 18), **LBD**: 52 (IQD 17)	Early subacute to chronic Initial: RBD: 31 (IQD 15), LBD: 21 (IQD 9) days; also at 3 and 6 months	Bell's test, LBT, CBS, baking tray task, animals test (Combined Index of Neglect Severity)	Combined Index of Neglect Severity was computed. Index ranged from 0 to 5, with 0 indicating no evidence of SN in any of the tests and 5 indicating SN in all tests. Score >2 indicated SN
Bonan et al. (2007) [8]	C: pro	**RBD (n=14)**: SN+ (n=8), SN- (n=6); **LBD (n=14)**: SN+ (n=0), SN- (n=14)	**RBD±LBD:** 57.5 (IQD 22)	Early subacute and chronic 22.5 (IQD 33) days, at 6 months	Bell's test, LBT, scene copy test	SN when difference between the bells omitted on the left and right sides in the Bell's Test was >3, when bias in LBT was >0.6 cm and when at least one element was omitted in the scene copy test
Braem et al. (2014) [27]	CS	**RBD (n=16)**: SN+ (n=10), SN- (n=6)	SN+: 63.8 (SD 11.4), SN-: 57.3 (SD 15.8)	Early and late subacute *SN+: 7.4 (SD 2.0), SN-: 12 (SD 5.3) weeks*	Bell's test, LBT, scene copy test	SN when ≥ 2/3 tests indicated SN
Fukata et al. (2020) [28]	CS	**RBD (n=43)**: SN+LP- (n=10), SN+LP+ (n=11), SN-LP- (n=12), SN-LP+ (n=10)	SN+LP-: 63.9 (SD 12.9), SN+LP+: 70.1 (SD 10.4), SN-LP-: 65.4 (SD 10.8), SN-LP+: 66.3 (SD 12.4)	Early subacute SN+LP-: 14.0 (SD 6.6), SN+LP+: 14.0 (SD 8.3), SN-LP-: 15.2 (SD 5.0), SN-LP+: 12.1 (SD 4.7) days	Behavioral inattention test - conventional subtest	Score ranges from 0 to 146 points, with a score ≤131 indicative of SN
Funk et al. (2010) [29]	CS	**RBD (n=20):** SN+ (n=20), SN- (n=0)	SN+: 57 (*SD 12*)	Early subacute SN+: 2.5 (*SD 1.6*) months	LBT, star cancellation, letter cancellation, neglect-sensitive reading test	Cutoffs: deviations >5 mm from midpoint of 20 cm line in LBT, >4 omissions in star cancellation and letter cancellation tests, and >2 omissions/-substitutions of letters/ words and/ or prolonged reading time (>40 s).
Kerkhoff et al. (1998) [30]	CS	**RBD (n=27)**: SN+ (n=13), SN- (n=14); **LBD (n=14)**: SN+ (n=3), SN- (n=11)	**RBD:** SN+: 52.8, SN-: 45.8; **LBD:** SN+: 52.7 *(SD 9.7)*, SN-: 50.7 (other SD's NM or calculable)	Late subacute to chronic **RBD:** SN+: 6.2, SN-: 4.5; **LBD:** SN+: 8.0 *(SD 4.3)*, SN-: 5.0 months (other SD's NM or calculable)	Representational drawing, LBT, number cancellation task, copying task (daisy, face, house)	NM
Lafosse et al. (2004) [31]	CS	**RBD (n=43):** SN+ (n=31), SN- (n=12)	Mild SN+: 71.8 (SD 7.3), moderate SN+: 61 (SD 10.1), severe SN+: 66 (SD 8.3), SN-: 58 (SD 7.8)	Chronic Mild SN+:20.4 (SD 9.7), moderate SN+: 21.3 (SD 11.4), severe SN+: 15 (SD 11.2), SN-: 15.3 (SD 8.4) months	Behavioral inattention test - conventional subtest (SN severity: mild 89-129, moderate 70-90, severe <70)	SN if aggregate score < 129. Further classified in four groups, according to severity of SN: mild 89-129, moderate 70-90, severe <70
Mori et al. (2021) [32]	CS	**RBD (n=28):** SN+ (n=17), SN- (n=11); **LBD (n=15)**: SN+ (n=0), SN- (n=15)	**RBD+LBD:** SN+: 67.1 (SD 8.0), SN-: 63.8 (SD 10.4)	Early subacute SN+: 14.9 (SD 7.7), SN-: 9.8 (SD 4.7) days	LBT, star cancellation task, flower copying task	SN when at least 1 test exceeding the cut-off. Cut-off scores: LBT: ≤7 points, star cancellation: ≤ 51 points and ≥3 asymmetry points star cancellation task, copying task: 0 points
Pérennou et al. (1998) [11]	CS	**Stroke (n=22)** (number of SN+/- NM)	58.3 (SD 2.5)	Early subacute 83.2 (SD 10.7) days	Cancellation task	NM
Rousseaux et al. (2015) [33]	CS	**RBD (n=46):** SN+ (n=25), SN- (n=21)	RBD: 60.9 (SD 13.2)	Early subacute 43.3 (SD 30.2) days	LBT, scene copying test, bell's test	SN when performance was pathological in >2/3 tests. Cut-off scores: LBT rightward deviation>11%, scene copying score >1 out of 4 and bell cancellation left omissions >2 out of 15
Utz et al. (2011) [34]	CS	**RBD (n=32):** SN+ (n=16), SN- (n=16)	**RBD:** SN+: 71 (range 52-86), SN: 70 (range 47-84)	Early subacute SN+: 78 (SD 53.02), SN-: 61 (SD 79.91) days	LBT, letter cancellation test, star cancellation test, figure copying, paragraph reading, number cancellation test	SN when at least 3 tests exceeding the cut-off

C, cohort; CBS, Catherine Bergego Scale; CS, cross-sectional; IQR, interquartile range; LBD, left brain damage; LBT, Line bisection test; long, longitudinal; n, number; prosp, prospective; RBD, right brain damage; SN+, participants with spatial neglect; SN-, participants without spatial neglect. Underline, median values; italics, self-calculated mean values and standard deviations.

Table 2
Risk of bias according to the Newcastle-Ottawa Scale.

Risk of bias of cross-sectional studies	Selection				Comparability	Outcome		Total score	MQ
	1	2	3	4	1	1	2		
Baier et al. (2012) [25]	*		*	*			*	4/10	Poor
Barra et al. (2009) [26]	*		*	*			*	4/10	Poor
Braem et al. (2014) [27]			*	**	**			5/10	Mod
Fukata et al. (2020) [28]				**	**			4/10	Poor
Funk et al (2010) [29]			*	**			*	4/10	Poor
Kerkhoff et al. (1998) [30]	*			*	**		*	5/10	Mod
Lafosse et al. (2004) [31]			*	**	*		*	5/10	Mod
Mori et al. (2021) [32]			*	**	**		*	6/10	Mod
Pérennou et al. (1998) [11]				*	**			3/10	Poor
Rousseaux et al. (2015) [33]		*		**	**	**		7/10	Good
Utz et al. (2011) [34]		*		**	**		*	6/10	Mod
Risk of bias of longitudinal cohort studies									
Bonan et al. (2006) [15]	*	*	*	*	*	*	*	7/8	Good
Bonan et al. (2007) [8]	*	*	*	*	*	*	*	7/8	Good

Mod, moderate; MQ, methodological quality.

Battery [28,31]. The 2 remaining studies assessed multiple types of SN using the Catherine Bergego Scale (an ecological assessment tool for SN [35]) or a behavioral scale, combined with paper-and-pencil tests [26]. Considering the time post-stroke, the early subacute phase (1 week to 3 months post-stroke) was most frequently evaluated.

Risk of bias

The methodological quality of 3 studies was good [8,15,33], 5 moderate [27,30-32,34] and 5 poor [11,25,26,28,29] (Table 2). Each study received at least one star on the item that assesses ascertainment of exposure, which evaluates whether a validated SN tool was used, with or without the description of a cut-off value. In contrast, none of the studies received a star on the "assessment of outcome" item, which evaluates whether the outcome was assessed in a double-blinded fashion.

Measurement methods of verticality perception

Details regarding measurement methods (e.g., position, fixation during measurement, number of trials) are in Table 3.

SVV (Table 4)

For constant errors, 4 studies (2 good quality, 2 moderate quality) showed significantly larger magnitudes of tilt in SN than non-SN participants [15,30,33,34], whereas 2 (one poor quality, one moderate quality) did not find a difference between groups [28,32]. The more severe the SN on the Catherine Bergego Scale (activities of daily living-related scale), the more tilted the SVV ($r = -0.623$, $p = 0.002$, [95% confidence interval -0.827; -0.272]) [26]. In contrast, results were inconclusive regarding the correlation of the SVV with SN severity on a cancellation task [25,26], with no significant correlation with SN severity on a line bisection task [26]. Tilts were mainly evaluated in the subacute post-stroke phase (i.e., first week to 6 months). Only one study (good quality) evaluated the chronic phase, showing that the association between SN and SVV misperception disappeared [15]. However, only 3 participants still showed SN at this time [15]. Two studies evaluated unsigned errors and reported higher tilts in SN than non-SN participants, in both the early subacute phase [8,34] and chronic phase post-stroke [8].

Six studies reported magnitudes of tilts [8,27,28,30,32,34] and found that magnitudes were larger in participants with than without SN. Magnitudes ranged from a mean/median (SD) of -8.9° (32) to -2.3° (28) in SN participants and from -1.6° [32] to 0.6° [34] in non-SN participants. The presence of lateropulsion did not increase the magnitude of tilts [28]. The reported mean/median magnitudes of tilt were beyond the normative range in participants with SN in 4 studies and therefore were considered biased tilts [8,27,30,34]. For non-SN participants, tilt magnitudes were always within this range [8,27,28,30,32,34] and therefore were not considered biased. In most studies, the direction of tilt was reported as contralesional in SN participants (i.e., leftward tilt in right-side strokes) [27,30,33,34]. Two studies also reported ipsilesional tilts in some SN participants [28,32]. In non-SN participants, the tilt was not larger than 0° [27,34], whether contralesional [28,30] or ipsilesional [28,30,32].

Uncertainty was higher in SN participants (from a mean of 2.0° [30] to 8.8° [32]) than in non-SN participants (from 0.3° [30] to 1.6° [8]) [8,15,28,32]. Uncertainty increased if SN and lateropulsion were simultaneously present (U = 7.6°) [28].

SPV (Table 5)

Of the 3 studies evaluating SPV, 2 (poor quality) found no association between SN and SPV misperception [11,28] in the early subacute phase post-stroke, whereas one (moderate quality) found an association in the chronic phase [31]. When an association was present, tilts were larger in SN than non-SN participants (V = 0.2-0.4°) but only with moderate (V = -3.7°) to severe (V = 0.7°) SN [31] or when lateropulsion was present in addition to SN (V=2.1°) [28]. SPV it could not be evaluated whether the magnitudes of tilt were within or outside of normative limits for SN participants because of conflicting evidence; the magnitudes of tilt fell within the normative range for non-SN participants and were therefore not considered biased tilts [28,31].

For both SN and non-SN participants, we could draw no conclusions on the direction of tilt considering that both ipsi- and contralesional tilts were reported [11,28,31]. Uncertainty was evaluated by Fukata et al. [28], who showed no difference between SN (U= 4.0°) and non-SN participants unless lateropulsion was present in addition to SN (U=6.6°).

SHV (Table 6)

Four studies (one poor quality [29], 2 moderate quality [27, 34], one good quality [33]) evaluated the association between SN and SHV misperception. We found no significant difference in magnitudes of tilt between SN (V = -5.9°) and non-SN groups (V = -4.9°) [33,34]. For both SN and non-SN groups, mean tilts were considered biased because they were outside of reported normative values [27,34]. The direction of tilt was always contralesional in SN participants and for non-SN participants not significantly larger than 0° [34] or also

Table 3
Measurement information.

Author	Measurement method and outcomes	Participant setting	Task	N of trials with starting positions
SVV				
Baier et al. (2012) [25]	Special goggles (ATHERMAL® GSF 166 DIN) that only show luminous rod of 29.5 cm, 1 cm width. V evaluated.	Seated in chair, 1.5 m distance to line, non-fixed head (participants were instructed to keep head upright), head position water level controlled.	Examiner oriented line until participant indicated it as vertical.	12 (random): 2 with line oriented at 20°, 30° or 40° to CW and CCW.
Barra et al. (2009) [26]	Dark room, luminous rod of 15 cm, 0.2 cm width, masked surround on a computer screen. V evaluated.	1.5 m distance to line, participant position and fixation NM.	Examiner oriented line until participant indicated it as vertical.	10 (pseudo-random): balanced between CCW and CW.
Bonan et al. (2006) [15]	Dark room, luminous rod of 30cm. V and U (range) evaluated.	Seated in (wheel)chair, 2 m distance to line, non-fixed head.	Participant adjusted line to vertical by manipulating a box held in non-paretic hand. No time limit.	6 (3 series): in each series: 1 with rod oriented 60°CCW, 1 with rod oriented 60°CW.
Bonan et al. (2007) [8]	Dark room, white line on dark background. V and U (SD) evaluated.	Seated in (wheel)chair, 2 m distance to line, fixed head (chin rest).	Examiner oriented line until participant indicated it as vertical. No time limit.	8 (random): 4 with line oriented 40° to CCW, 4 with line oriented 40° to CW.
Braem et al. (2014) [27]	Dark room, rod of 25 cm with red LEDs. V evaluated.	Seated in bed, 0.4 m distance to line, fixed head (strap).	Examiner oriented line until participant indicated it as vertical. No time limit.	4 (random): 2 with line oriented 45° CCW, 2 with line oriented 45°CW.
Fukata et al. (2020) [28]	Participant viewed computer display through a cylindrical tube to obscure frame and remove visual cues. V and U (SD) evaluated.	Seated on chair, 0.5 m distance to line, feet flat on floor, fixed trunk (belts), non-fixed head (maintained freely upright).	Visual indicator oriented line at 5°/s by computer until participant indicated it as vertical (stopped by examiner).	8 (ABBABAAB sequence): during A, the line was oriented CCW; during B, the line was oriented CW (degrees not provided).
Kerkhoff et al. (1998) [30]	Dark background, white line of 18 cm, screen borders were hidden behind an oval-shaped mask. V and U (DT) evaluated.	0.5 m distance to line, fixed head and trunk (head-and-chin rest).	Examiner oriented line until participant indicated it as vertical, and then further until participant indicated that it is no longer vertical. No time limit.	Initial deviation 15° from vertical (CCW and CW).
Mori et al. (2021) [32]	Dark room, luminous line of 30 cm on screen, projected with hidden borders. V and U (SD) evaluated.	Seated, 1 m distance to line, fixed head and trunk (belts and cushions).	Examiner oriented line until participant indicated it as vertical. No time limit.	10 (random): 5 deviated 30°CCW, 5 deviated 30°CW. Beforehand 1 practice trial in a light room.
Rousseaux et al. (2015) [33]	Dark room, rod of 25 cm with 10 red light-emitting diodes. V evaluated.	Seated semi-recumbent on treatment table, 0.5 m distance from rod, fixed head and trunk (straps).	Examiner oriented line until participant indicated it as vertical. No time limit.	18 (2 per rod starting positions (n=3) and starting angles (n=3)): rod fixed on midsagittal plane of participant, or 15 cm left or right from participant. Starting angles: -45°, 0°, +45°.
Utz et al. (2011) [34]	Dark room with darkened box in which measurement took place, rod of 21.5 cm illuminated in red. V evaluated.	Seated, 0.4 m distance to line, fixed head (head-and-chinrest).	Participant received visual input only participant oriented line by rotating disc beneath rod (no haptic cues on verticality) with non-paretic hand until perceived as vertical. No time limit.	72 (3 times 6 trials for every starting angle (n=2) and plane (n=2)).
SPV				
Fukata et al. (2021) [28]	Vertical board in bright room. V and U (SD) evaluated.	Seated on board, arms folded across chest, feet off ground, fixed trunk (belts), non-fixed head and legs.	Examiners deviated participant at +/- 1.5°/s until participant indicated position as vertical. 2 sessions.	8 (ABBABAAB or BAABABBA sequence): during A, the line was oriented CCW; during B, the line was oriented CW. Starting position: 15° or 20°.
Lafosse et al. (2004) [31]	Rotating chair. V evaluated.	Seated, hands crossed on thighs, lateral stabilization of participant, legs freely hanging, head fixation NM.	Examiner deviated participant until participant indicated position as vertical. 2 sessions.	6 (random): starting position at least 35°CCW or CCW.
Pérennou et al. (1998) [11]	Rocking platform (unstable in 0ML direction), rigid support mounted on see-saw with horizontal rotation axis. V evaluated.	Seated centrally, no fixation, hands on thighs, legs freely hanging.	Examiners deviated participant until participant indicated position as vertical. 2 sessions.	NM
SHV				
Braem et al. (2014) [27]	Participant blindfolded, non-paretic hand on rod of 25cm. V evaluated.	Seated in hospital bed, 0.4m distance to line, fixed head (strap).	Participant oriented rod until perceived as vertical. No time limit.	4 (random across participants): 2 with rod oriented 45°CCW, 2 with line oriented 45°CW.
Funk et al. (2010) [29]	Participant blindfolded, non-paretic hand on rod of 15cm. V and U (range) evaluated.	Seated on chair, fixed head (head-and-chinrest) + lying on medical stretcher.	Participant oriented rod until perceived as vertical. No time limit.	Seated and lying (each): 10 (random): 5 with rod oriented 40°CCW, 5 with line oriented 40°CW.
Rousseaux et al. (2015) [33]	Participant blindfolded, non-paretic hand on rod of 25cm. V evaluated.	Seated semi recumbent on treatment table, 0.5 m distance to rod, fixed head and trunk (straps).	Participant oriented rod until perceived as vertical. No time limit.	18 (2 per rod starting positions (n=3) and starting angles (n=3)): rod fixed on midsagittal plane of participant, or 15 cm left or right from participant. Starting angles: -45°, 0°, +45°.
Utz et al. (2011) [34]	Participant blindfolded, non-paretic hand on rod. V evaluated.	Seated, 0.4m distance to rod, fixed head (head-and-chinrest).	Participant oriented rod until perceived as vertical. No time limit.	18 (2 per rod starting positions (n=3) and starting angles (n=3)): rod fixed on midsagittal plane of participant, or 15 cm left or right from participant. Starting angles: -45°, 0°, +45°.

CCW, counterclockwise; CW, clockwise; DT, difference threshold; ML, mediolateral; NM, not mentioned; SHV, subjective haptic vertical; SPV, subjective postural vertical; SVV, subjective visual vertical; U, uncertainty; V, tilt.

Table 4
Subjective visual vertical (results).

Author	MQ	Statistics	Values (V and U in ° [SD]), direction of deviation	Results for magnitude of deviation (V)	Results for uncertainty (U)
Baier et al. (2012) [25]	Poor	Pearson correlation	*NM*	*More severe neglect score (Bell's test CoC) is correlated with higher magnitude of deviation (r=0.487, p<0.001, CI NM)*	*NA*
Barra et al. (2009) [26]	Poor	NM	Direction: 6 out of 22: ipsilesional; 16 out of 22: contralesional. Unknown who show SN, as there are no cut-off values for SN reported.	Sig correlation of SVV and CBS score (r=-0.623, p=0.002, [-0.827; -0.272]). No sig correlation with the LBT (r=-0.209, p=0.350, [-0.580; 0,233]) and Bell's test (r=-0.15, p=0.491, [-0.541; 0.285])[A]	NA
Bonan et al. (2006) [15]	Good	Mann-Whitney U, spearman correlation	*RBD and LBD: CL (2 RBD: IL, unknown whether these showed SN)*	*Baseline: sig larger deviations in SN+ than SN- group (p=0.01, CI NM);* *3 months: sig larger deviations in SN+ than SN- group (p=0.04, CI NM);* *6 months: no sig difference between SN+ and SN- (p=0.1, CI NM), but only 3 participants showed SN))*	*Baseline: sig higher uncertainty in SN+ than SN- group (p=0.002, CI NM)* *3 months: sig higher uncertainty in SN+ than SN- group (p=0.004, CI NM)* *6 months: no sig difference between SN+ and SN- (p=0.07, CI NM), but only 3 participants showed SN)*
Bonan et al. (2007) [8]	Good	Mann-Whitney U, Kendall coefficient correlation	*Baseline: SN+: V=5.4° (IQR 5.0°), U=6.5° (IQR 4.9°); SN-: V=1.9° (IQR 3.5°), U= 1.6° (IQR 1.8°)* *6 months: SN+: V=3.2° (IQR 1.7°), U=3.2° (IQR 2.0°); SN-: V=1.7°(IQR 2.0°), U=1.5° (IQR 1.0°)* *Direction: NA (unsigned errors)*	*Unsigned errors* • *Baseline: sig higher magnitude in SN+ than SN- group (p=0.02). SN and V: Sig correlation (r NM, p=0.02, CI NM)* • *6 months: sig larger deviation in SN+ than SN- group (p=0.04, CI NM)*	*Unsigned errors:* • *Baseline: sig difference between SN+ and SN- groups (p=0.005). Sig correlation between SN and uncertainty (r NM, p≤0.01, CI NM)* • *6 months: sig larger uncertainty in SN+ than SN- group (p=0.01, CI NM)*
Braem et al. (2014) [27]	Mod	ANOVA with Newman-Keuls post-hoc	SN+: V=-3.9° (SD 4.14°), CL direction; SN-: V=0.5° (SD 3.7°), direction NS	SN+: p-value and CI NM SN-: p-value and CI NM	NA
Fukata et al. (2020) [28]	Poor	ANOVA with Bonferroni post-hoc, pearson correlation	SN+LP-: V=-2.3° (SD 3.7°), CL direction in 6 participants, IL direction in 2 participants, U=6.9° (SD 5.9°); SN+LP+ (V=-1.4° (SD 5.1°)), CL direction in 7 participants, IL in 4 participants, U=7.6° (SD 6.3°); SN-LP-: V=-0.6° (SD 2.2°), CL direction in 7 participants, IL direction in 5 participants, U=1.4° (SD 0.6°); SN-LP+ : V=1.5° (SD 5.7°), IL direction in 4 participants, CL direction in 5 participants, U=1.9° (SD 0.5°)	No sig difference between groups (p-value and CI NM)s	Sig higher uncertainty in SN+LP+ and SN+LP- than in SN-LP+ and SN-LP- groups (p<0.05). Uncertainty was sig correlated with the BIT score (r=0.752, p<0.001, CI NM)
Kerkhoff et al. (1998) [30]	Mod	ANOVA with Scheffé post-hoc	*RBD SN+: V= -4.9° (SD 3.8°), U=2.0° (SD 3.87°);* *RBD SN-: V=-0.2° (SD 0.5°), U=0.3° (SD 0.5°);* *LBD SN-: V=-0.4° (SD 0.8°), U=0.6° (SD 1.0°);* SN+: CL direction, SN-: IL direction (LBD SN+ group not included in statistics)	RBD SN+ group had sig larger deviations than RBD SN- and LBD SN- groups (p<0.05, CI NM). No main effect of 'Rotation direction'	Sig group effect (F=23.11, p<0.0001, CI NM), post-hoc test not performed (CI NM)
Mori et al. (2021) [32]	Mod	One-sample T-tests, ANOVA with Tukey HSD post-hoc	SN+: V=-2.1° (SD 3.7°), U=8.8° (SD 5.2°); SN-: V NM; U=1.9° (SD 1.1°) Group x direction interaction effect: **SN+** : CL direction: V=-8.9° (SD 5.9°), U= 4.4° (SD 3.7°), IL direction: V=-4.7° (SD 6.1°)), 4.6° (SD 3.5°); **SN-** : CL direction: V=-1.6° (SD 3.0°), 0.8° (SD 0.5°), SN- IL: V=-0.8° (SD 3.7°), 1.0° (SD 0.6°). SN+: CL direction; SN-: direction NS Direction: generally CL, however, individual data shows IL tilt in 7 out of 17 SN+ participants, and 10 out of 26 SN- participants	Sig difference between groups (F=3.2, p=0.046, CI NM), but post-hoc tests showed no sig differences between SN+ and SN- groups Sig group x direction interaction effect (F=3.4, p=0.035, CI NM): sig larger magnitude of deviation in relation to initial starting position in SN+ than SN- group. Starting direction influenced the results: SVV was more deviated if started from CL side compared to IL side (p=0.015, CI NM)	Uncertainty was sig higher in SN+ than in SN- group (p<0.001, CI NM) Sig group effect (F=58.6, p<0.001, CI NM), no direction effect (F=0.3, p=0.61, CI NM) or interaction between these factors (F=0.0, p=0.99, CI NM). SN+ group had sig higher uncertainty when starting position was considered compared to SN- group (p<0.001, CI NM)
Rousseaux et al. (2015) [33]	Good	Chi-square test, Spearman correlation test	*CL direction*	*Sig larger deviation in SN+ than in SN- group (values NM, p=0.047, CI NM). A total of 21 participants (of whom 16 with SN) exceeded the cut-off (-2.6°) for a "true" deviation.*	NA
Utz et al. (2011) [34]	Mod	ANOVA with post-hoc Bonferroni test, one-sample T tests	Constant errors: SN+: V=-3.0° (SE 2.0°), CL direction; SN-: V=0.6° (SE 1.0°), direction NS; Unsigned error: SN+: V=5.0° (SE 1.4°); SN-: V=1.3° (SE 1.3°)	Constant errors: sig larger deviations in SN+ than SN- groups (p<0.04, CI NM). Unsigned errors: sig larger deviations in SN+ than SN- group (p=0.003, CI NM).	NA

CBS, Catherine Bergego Scale; CI, confidence interval; CL, contralesional; IL, ipsilesional; IQR, interquartile range; LBD, left brain damage; MQ, methodological quality; NA, not applicable; NM, not mentioned; RBD, right brain damage; SE, standard error; sig, significant; SN+, spatial neglect; SN-, no spatial neglect; SVV, subjective visual vertical; U, uncertainty; V, (magnitude of) deviation. Italics, median values and non-parametric statistics. [A] implies self-calculated values and/or statistics.

Table 5
Subjective postural vertical (results).

Author	MQ	Statistics	Values (V and U in ° [SD]), direction of deviation	Results for magnitude of deviation (V)	Results for uncertainty (U)
Fukata et al. (2021) [28]	Poor	ANOVA with Bonferroni post-hoc	**SN+LP+:** V=-2.1° (SD 2.0°), CL direction in 9 participants, IL direction in 2 participants, U=6.6° (SD 2.0°); **SN-LP+:** V=-2.2° (SD 1.1°), CL direction, U=6.3° (SD 1.4°); **SN+LP-:** V=-0.2° (SD 1.4°), CL direction in 5 participant, IL direction in 4 participants, U=4.0° (SD 1.8°); **SN-LP-:** V=-0.4° (SD 1.0°), CL direction in 7 participants, IL direction in 5 participants, U=3.5° (SD 1.0°);	Sig larger deviations in SN+LP+ and SN-LP+ than in SN+LP and SN-LP- groups (p<0.05, CI NM)	Sig higher uncertainty in SN+LP+ and SN-LP+ than SN+LP- and SN-LP- groups (p<0.05) (CI NM)
Lafosse et al. (2004) [31]	Mod	ANOVA	**SN-:** V=0.3°, direction NS; **Mild SN+:** V=2.0°, IL direction; **Mod SN+:** V=3.7°, IL direction; **Severe SN+:** V=-0.7°, CL direction	Mod SN+ sig larger deviations compared with SN- group (p< 0.001, CI NM); Severe SN+ sig larger deviations than mod SN + (p<0.001, CI NM)	NA
Pérennou et al. (1998) [11]	Poor	Correlation analysis (type NM)	CL direction	No sig correlation with magnitude of deviation and SN severity (p>0.05, CI NM)	NA

CI, confidence interval; CL, contralesional; Mod, moderate; MQ, methodological quality; NA, not applicable; NM, not mentioned; NS, not significant; LP, lateropulsion; sig, significant; SN+, spatial neglect; SN-, no spatial neglect; U, uncertainty; V, mean deviation; negative values indicate a counterclockwise deviation.

contralesionally deviated [27,33]. In contrast to constant errors, unsigned errors were significantly higher for SN than non-SN participants (V = 7.1° vs 4.1°) [34].

Only Funk et al. (poor quality) evaluated the correlation between SN severity and SHV misperception and showed that more cancellation errors and line bisection errors related to significantly higher SHV misperception [29]. The study was also the only one to investigate uncertainty, showing that more errors on the star cancellation test were significantly correlated with higher uncertainty [29]. Only the early and late subacute phases were evaluated.

Discussion

The aim of this study was to systematically analyze the reported associations between SN and the perception of verticality while considering the time post-stroke. If methodological quality is considered, the evidence points toward larger SVV tilts and uncertainty in SN as compared with non-SN participants in the first 3 to 6 months post-stroke. In contrast, we could draw no conclusions on the SPV and SHV modalities because of the few studies investigating these modalities and often low methodological quality.

Table 6
Subjective haptic vertical (results).

Author	MQ	Statistics	Values (V and U in ° [SD]), direction of tilt	Results for magnitude of tilt (V)	Results for uncertainty (U)
Braem et al. (2014) [27]	Mod	ANOVA with Newman-Keuls post-hoc	SN+: V=-5.9° (SD 4.3°); SN-: V=-4.9° (SD 4.6°); SN+ and SN-: CL direction	P-value of between-group comparison NM.	NA
Funk et al. (2010) [29]	Poor	Spearman and Pearson correlations	CL direction	No sig correlation between SN severity (sum of tests with values above cut-off) and constant errors (r=0.21, p>0.15) or unsigned errors (r=0.21, p>0.15) (CI NM) Constant errors were sig correlated with star cancellation (r=0.57, p<0.01), E&R cancellation (r=0.53, p<0.05) and LBT (r=0.54, p<0.05); not with reading errors (r=-0.07, p>0.05) (CI NM) Unsigned errors were sig correlated with star cancellation (r=0.61, p<0.01) and E&R cancellation tests (r=0.59, p<0.01); not with LBT (r=0.42, p<0.05) and reading errors (r=0.21, p>0.05) (CI NM)	Sig correlation between SN severity (sum of tests with values above cut-off) and uncertainty (r=0.33, p<0.09, CI NM) Uncertainty was sig correlated with star cancellation (r=0.67, p<0.01); not with E&R cancellation, LBT and reading errors (r=0.63, r=0.19 and r=0.42, p<0.05 respectively) (CI NM)
Rousseaux et al. (2015) [33]	Good	Chi-square test, Spearman correlation test	SN+ and SN-: CL direction	No sig difference between SN+ and SN- groups for magnitude of tilt (p=0.178, CI NM). Nine participants of whom 7 with SN exceeded the cut-off (CCW -9.8°) for a SHV tilt.	NA
Utz et al. (2011) [34]	Mod	ANOVA with post-hoc Bonferonni test, one sample T-test	Constant errors: SN+: V=3.0° (SEM 3.2°), CL direction; SN-: V=1.1° (SEM 1.8°), direction NS; Unsigned errors: SN+: V=7.1° (SEM 1.7°), SN-: V=4.13° (SEM 1.5°)	Constant errors: no sig difference in magnitude of tilts between SN+ and SN- group (p=0.25, CI NM) Unsigned errors: SN+ group had sig larger tilts compared to SN- group (p=0.02, CI NM)	NA

CI, confidence interval; CL, contralesional; LBT, Line Bisection Test; MQ, methodological quality; Mod, moderate; NA, not applicable; NM, not mentioned; NS, not significant; sig, significant; SN+, spatial neglect; SN-, no spatial neglect; SHV, subjective haptic vertical; V, mean deviation; negative values indicate a counterclockwise deviation.

The direction of tilt differs across studies, modalities assessed and measurement methods used. For the SVV, most studies report a contralesional deviation in SN participants; however, ipsilesional deviations were also reported. For SHV, there was agreement on a contralesional deviation in SN participants, but no conclusions could be drawn for SPV. For non-SN participants, the direction was also contralesional (with smaller magnitudes), ipsilesional or not significantly larger than 0°. Of note, for SVV, mean magnitudes of tilt were almost always outside the normative range for SN participants but within this range for non-SN participants (-2.5° to 2.5° [14,21]). This observation may indicate that a misperception of SVV is a key feature of SN, at least within the first 6 months post-stroke. Because of inconclusive evidence for the SPV and SHV conditions, no conclusions could be drawn about whether the constant errors of these modalities were within normal ranges. In addition, a lack of normative values for uncertainty measures also prohibits conclusions on these measures.

Studies predominantly evaluated the subacute phase post-stroke (1 week to 6 months). Consequently, associations between SN and SVV misperception were strongest in this time phase as well. Because repetitive measurements of verticality perception from the early subacute to chronic post-stroke phase are lacking, investigating the recovery patterns of verticality misperception is difficult. However, the scant evidence points toward recovery from the subacute to chronic phases, both in SN and non-SN participants [8,15]. SN follows a natural logistic pattern of improvement within the first 12 to 14 weeks post-stroke, after which the recovery curve plateaus [36]. Because of a lack of longitudinal studies, one cannot evaluate whether the recovery of verticality misperception shows a similar pattern.

Studies exhibited methodological differences that may account for some inconclusive evidence, such as SN assessment methods and verticality testing procedures. In all but 2 studies, SN was evaluated solely by paper-and-pencil tests. These tests are not sensitive enough to evaluate the complexity of SN because they are easily compensated for in mild or even moderate SN [37]. In addition, they mainly assess visuospatial neglect and do not sufficiently address other SN types (e.g., personal, motor, tactile neglect). Mainly visuo-spatial neglect being evaluated may also contribute to the observation that primarily the SVV is affected in SN participants. Indeed, visuo-spatial neglect implies neglect for visual stimuli, and the perception of the visual vertical relies primarily on visual input. For SPV and SHV, visual input is eliminated and does not contribute to the outcome.

With regard to the verticality testing procedures, a crucial factor to consider is head fixation. Without fixation, head tilts can occur and could induce the “E-effect” [38,39], which implies a tilt of the subjective vertical toward the opposite side of the starting head-on-body position. The E-effect was previously shown to exist for the SVV and SPV modalities [38,39]. A lack of fixation can decrease the accuracy of the measurements because the individual can perform compensatory head movements [21,38,40], possibly ameliorating their result [11,28,31]. Head (and trunk) fixation is especially necessary in participants who are unable to sit independently, which is often the case in participants with SN in the early subacute phase [41].

Limitations

The sample sizes were small, which limited not only statistical analyses but also the interpretation and generalization of results. Because of this, we could evaluate only associations between SN and misperception of verticality, and not causality. Consequently, the suggested interpretation of the existence of a “graviceptive neglect” (see Introduction) cannot be answered or refuted by this systematic review [4,6,11,12].

Variability was high for characteristics of included participants, use of SN assessment tools, SN cut-offs, time points of assessment, measurement methods used and sample sizes across studies, which questions the robustness of the results of this review. However, most studies focused on one subtype of SN, namely visuospatial neglect. Even though heterogeneity was present, results were relatively consistent within the SVV modality, thus pointing toward SVV misperception being a potential key feature of SN.

Additionally, the generalizability of this review may be affected by the absence of geographical diversity considering that most included studies were performed in high-income countries and by members of the same research groups. However, we tried to reduce the impact of this bias by excluding studies with an overlap in sample series. An overview of the studies with series overlap can be found in the Supplementary E-files. Tables, Full-text exclusions with reasons and Series overlap.

Because lesion information was not considered, this review was unable to agree with or refute the first and second interpretation that was proposed to explain a potential association of SN with verticality misperception, described in the Introduction. Including such information would have provided valuable insight into verticality misperception mechanisms, which should be encouraged in further research. Another limitation is the consideration of articles solely written in English.

Clinical implications and suggestions for further research

Evidence suggests that SN is associated with SVV misperception and that SVV misperception could even be considered a key feature of SN. The importance of accurate verticality perception for postural control [8,9] calls for a systematic and regular assessment of SVV perception in clinical practice, as an addition to standard SN assessment.

Most studies have a cross-sectional study design and do not allow for evaluating the recovery of verticality misperception in SN participants. In the longitudinal studies included, time intervals were broad ($\geq$ 3 months) [8,15]. Future studies should evaluate the association of recovery of SN with recovery of verticality misperception over time by systematically evaluating participants with SN at regular times from the acute to chronic phases post-stroke.

A more comprehensive assessment of SN, using more than solely paper-and-pencil tests that mainly evaluate visuo-spatial neglect, is warranted. Currently, we do not know whether verticality misperception is expressed similarly across the different SN types (i.e., motor neglect, auditory neglect, personal neglect). Also, the assessment of additional deficits, such as lateropulsion, should be encouraged.

Conclusion

In the first 3 to 6 months post-stroke, SN is associated with larger SVV tilts falling outside of normative ranges, together with higher SVV uncertainty as compared with non-SN participants. This observation suggests that SVV misperception is a key feature of SN. For SPV and SHV, the evidence was insufficient or inconclusive, which may also result from these conditions being highly under-investigated as compared with SVV. Currently, the recovery of verticality misperception cannot be evaluated because of lack of longitudinal studies, which should be addressed by future studies.

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Conflict of interest

None declared

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rehab.2022.101700.

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