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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Psicologia da Saúde e Reabilitação Neuropsicológica, realizada sob a orientação científica do Doutor Nuno Alexandre de Sá Teixeira, Professor Auxiliar Convidado do Departamento de Educação e Psicologia da Universidade de Aveiro

Dedico este trabalho aos meus pais, Lúcia e Telmo, pois sempre foram o meu suporte nos momentos de maior dúvida e incerteza. Obrigada por estarem sempre comigo quando mais necessitava, e por acreditarem que era capaz. Esta é uma conquista nossa, e estarei sempre grata por todo o amor que me deram ao longo destes cinco anos.

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o júri

presidente

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palavras-chave

Orientação Espacial, Gravidade Representacional, Momento Representacional, Vector Idiotrópico, Força do Sinal de Movimento

resumo

A localização onde um objecto em movimento desaparece é percebida como desfasada para diante, na direcção do movimento (Momento Representacional; MR) e para baixo, na direcção da gravidade (Gravidade Representacional; RG). No que se refere à GR, estudos prévios sugerem que a direcção 'para baixo' é essencialmente determinada pela orientação do corpo do observador (vector idiotrópico). Contudo, um estudo prévio reportou resultados contrários, com maiores desfasamentos percebidos na direcção da gravidade, independentemente da posição do observador. Estes resultados opostos podem dever-se a várias diferenças metodológicas nas experiências conduzidas até ao momento, em particular o tipo de movimento do alvo – fluído ou aparente –, factor que se sabe afectar significativamente juízos de localizações espaciais. Por forma a clarificar este assunto, são aqui relatados os resultados de uma experiência em que a força do sinal de movimento (fluído vs aparente) foi factorialmente cruzado com a orientação do corpo dos observadores relativamente à vertical (sentados vs decúbito lateral) numa tarefa típica de localização espacial (usando uma trackball). Os resultados revelam que a GR depende do vector idiotrópico e não é modulada por sinais vestibulares, sendo que o tipo de movimento do alvo modula a magnitude, mas não a direcção, dos desfasamentos espaciais.

keywords

Spatial Orientation, Representational Gravity, Representational Momentum, Idiotropic Vector, Strength of the Motion Signal

abstract

The perceived offset of a moving target has been shown to be displaced forward, in the direction of motion (Representational Momentum; RM) and downward, in the direction of gravity (Representational Gravity; RG). Regarding RG, available evidence suggests that the 'downward' direction is chiefly determined by the orientation of the body's main axis (idiotropic vector). However, a previous study reports increased displacements along gravity's direction irrespective of the participants' body orientation. These disparate reports might be accounted for by several differences between the methodologies used, prominently the type of motion displays – smooth or apparent motion –, known to significantly modulate spatial localization judgements. To clarify this issue, we report the outcomes of one experiment where strength of the motion signal (smooth vs apparent) was factorially crossed with participants' body position relative to the vertical (upright vs left lateral decubitus) with a standard spatial localization task (using a trackball). Results reveal RG to be attached to the idiotropic vector and to be unaffected by vestibular signals, with motion type affecting the magnitude, but not the direction, of spatial displacements.

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Introduction

Given the known neural delays in relaying information (Nijhawan, 2008), particularly relevant when a moving object is being visually tracked, it has been suggested that the visual system actively attempts to calculate its future positions, extrapolating its motion into the immediate future. Moreover, the predictive utility in motion extrapolation could be greatly improved if the visual system takes advantage of environmental regularities by incorporating physical invariants, such as momentum and gravity (Hubbard, 2005). These ideas have been explored under the notion of internal models (Lacquaniti et al, 2013) and empirically linked with known perceptual effects, such as Representational Momentum and Representational Gravity.

Representational Momentum and Representational Gravity

When people are shown a dynamic event (e.g., a rectangular shape undergoing apparent rotation) which is suddenly halted and if required to provide a judgement concerning its last seen orientation, their responses betray a tendency to misperceive it going further, analogous to the effects of physical momentum and hence referred to as Representational Momentum (RM; Freyd & Finke, 1984; Kelly & Freyd, 1987; Reed & Vinson, 1996). In accordance with the momentum metaphor, RM is reliant on some conditions, such as the successive stimuli being coherent with a veridical trajectory and stimulus identity being preserved throughout the animation (Reed & Vinson, 1996). Similarly, the magnitude of RM is known to increase as a function of implied velocity (Freyd & Finke, 1985) and to possess a time course, increasing continuously until 300 ms, stabilizing for longer durations.

Although most classical studies measured RM with a mnesic probe methodology – where a static probe is shown in the spatial vicinity of the last location occupied by the target and participants required to provide a same/different judgement (commonly, they are more prone to accept as ‘same’ a probe further displaced in the direction of motion) –, later studies by Hubbard and collaborators successfully replicated it with small targets (e.g., a circle or a square) smoothly moving along a linear trajectory and requiring participants to directly locate its vanishing position (e.g., using a cursor controlled with a mouse; Hubbard & Bharucha, 1988; Hubbard, 1990). Due to the fact that a spatial localization response is not constrained to a dimension parallel to target’s trajectory but can also deviate orthogonally, in these later studies observers also showed a propensity to mislocalize moving targets downward, in the direction of gravity – this trend emerges both for targets moving horizontally, where people mislocalize its offset as below the actual trajectory, but also for targets moving vertically, with bigger RM for descending as compared with ascending targets. This related phenomenon was promptly coined Representational Gravity (RG) and thought to reflect the functioning of an internal model of earth's gravity. Importantly, and depending on the direction of target's motion, RM and RG may become intertwined (particularly for vertically moving objects), which prompted the adoption of the terms M-displacement and O-displacement, for the empirically measurable spatial displacement along the target's motion trajectory and orthogonal to it, respectively. These terms are meant to be atheoretical and merely descriptive, while the notion of RM and RG are reserved for theoretical explanations for those spatial localization errors.

Be it as it may, and in what refers specifically to RG (be it indexed by M-displacement for vertically moving objects or by O-displacements with horizontally moving targets) its standard definition – 'downward displacement in the direction of gravity' –, taken at its face value, seems to imply that observers would systematically misperceive a moving target's offset location as displaced along the environment's physical gravity. This prediction runs contrary to main findings reported in the literature on spatial orientation, briefly reviewed in what follows.

Spatial Orientation and the Subjective Vertical

The perceived direction of 'downward' as been a topic of active research since the seminal studies by Mittelstaedt (1983, 1986). Vestibular signals, chiefly from the otolithic organs (Mars et al., 2001), signal an inclination of an observer's head in relation to the gravitational acceleration, effectively acting as a tilt sensor. However, it is also the case that vestibular signals are subjected to considerable neuronal noise and its degree of reliability is far from ideal (Angelaki et al., 2009). Consequently, spatial orientation perception relies on other sources of information, such as bodily graviceptors, visual contextual cues and an aprioristic proclivity to assume that the vertical aligns with the body's longitudinal axis – so called, *idiotropic vector* (for instance, astronauts in microgravity, lacking otolithic signals and given an ambiguous visual context, tend to perceive as 'down' whichever surface located towards their feet; Oman, 2003; Clément & Reschke, 2008). As any of these cues (vestibular, somatosensory and visual) are independent of each other, albeit often with a certain degree of redundancy in natural contexts, depending on their relative implied directions the actual and perceived ‘downward’ might significantly differ (Glasauer & Mittelstaedt, 1992; MacNeilage et al., 2008; Zupan et al., 2002)

Commonly, how the perceptual system solves conflicts between orientation cues and how it integrates differing information concerning the perceived vertical, has been studied by measuring the subjective visual vertical: Observers are required to adjust (or, less often, to judge) the orientation of a visual rod so that it matches the world’s vertical (such that a ball dropped from the top end of the rod would fall along its extension). The adjustable rod might be embedded in a visual context more or less tilted in relation to the actual vertical or, importantly for the present purposes, while participants are themselves tilted sideways by varying amounts. In the latter scenario, a conflict between the vertical direction, as sensed by the vestibular system, and the idiotropic vector emerges, leading to errors in the adjustment of the visual rod of up to 40º or 50º, revealing a compromise between the two directions (Aubert Effect; reported originally by Aubert, 1861; see also De Vrijer et al, 2008, 2009; Mittelstaedt, 1986).

Representational Gravity and the Perceived Downward Direction

Given the multisensorial nature of the perceived vertical direction, particularly on what refers to its dependence on vestibular inputs and the idiotropic vector, one might ask how it modulates the direction on Representational Gravity. Some studies attempted to answer this question, by systematically changing the orientation of the observers’ bodies in relation to the actual vertical. Nagai and collaborators (2002) were the first to research this issue, across two experiments. In their first experiment, observers were positioned either in an upright or prone position, and shown a square successively occupying different locations on the screen resulting in an apparent motion either towards the direction of their feet or their heads. After each animation, one static square, occupying the same location were the target vanished or slightly more displaced forward or backward was shown and participants required to provide a ‘same’/’different’ location judgement. Participants accepted more often as ‘same’ a probe further displaced in the direction of motion for descending, in comparison with ascending, targets but only when they were upright (notice that, when in a prone position, the target was shown moving along a trajectory orthogonal to the actual gravitational pull). In their second experiment, everything was similar except for the motion of the target which was shown looming or receding, such that its implied motion was now aligned with physical gravity but orthogonal to it for the prone or upright postures, respectively. Bigger perceived displacements in the direction of actual gravity were, once again, found. The overall conclusion was that RM was consistently bigger for objects moving along the direction of actual gravity, irrespective of the participants body orientation, presumably to a vestibular dominance and seemingly in accordance with the core tenet of RG.

In a later sequence of studies, De Sá Teixeira and collaborators investigated the role of gravitational and idiotropic vectors in the determination of RG, using as stimuli targets moving smoothly along a linear trajectory and gauging spatial localization errors by requiring participants to adjust a visual cursor with a mouse or trackball to the perceived offset position of the target, after an imposed retention interval. In the report by De Sá Teixeira and Hecht (2014), using targets moving horizontally or vertically on an upright screen (that is, parallel to the frontal plane) with participants in an upright or left lateral decubitus posture, RG was found to be locked to the idiotropic vector, with bigger displacements consistently being found for targets moving towards participants' feet. On the other hand, the commonly found temporal course for RG, where its magnitude increases with increasing temporal intervals, was found solely for the upright posture, being null for the decubitus position. The outcomes were interpreted as evidence that RG's direction is determined solely by the idiotropic vector but its time course to depend on the degree of conflict between vestibular signals and the idiotropic vector. The same results were replicated by De Sá Teixeira (2014), with participants' bodies being oriented either upright or with a 22.5º, 45º, 67.5º or 90º tilt in relation to the vertical (with stimuli being shown in a Head Mounted Display which obstructed any visual cues from the laboratory room). RG's direction was found to be, once again, locked to the participants' bodies but its time course to be progressively reduced the farther their bodies deviated from the world's vertical. A similar result was found when participants' bodies were kept upright, but subjecting them to an artificial gravity environment by accelerating them more or less on a human centrifuge (thus resulting in an apparent tilt – somatogravic illusion; De Sá Teixeira et al., 2016).

The Present Study

It is still to be fully understood under which conditions or due to what factors a vestibular (as found by Nagai et al., 2002) or idiotropic dominance (as reported by De Sá Teixeira and collaborators) determines RG's direction. Focusing on methodological differences between those studies, conspicuous differences include the use of a mnesic probe methodology, where participants provide a ‘same’/’different’ judgement, or a spatial localization task, where participants adjust the location of a cursor with a computer mouse/trackball, and the strength of the motion signal, using either apparent or smooth motion. Importantly, both these factors have also been related to the role of eye movements on RM – whereas RM does not seem to depend on oculomotor behavior with apparent motion displays, irrespective of the response modality (Freyd & Finke, 1984; Freyd & Johnson, 1987; Kerzel, 2003, 2003a; but see; Kerzel, 2002), constraining eye movements significantly reduces or even eliminates RM for smoothly moving targets (Kerzel, 2000; Kerzel et al., 2001; De Sá Teixeira et al., 2013; De Sá Teixeira, 2016a), albeit less so for direct motor localization responses (Müsseler et al., 2002; Kerzel, 2003, 2003b; but for exceptions see Kerzel, 2000; Kerzel et al., 2001; De Sá Teixeira et al., 2013; De Sá Teixeira, 2016). On the other hand, eye movements do not seem to be involved in determining RG or its time course, although both increase when participants perform a perceptual task (mnesic probe; De Sá Teixeira et al, 2019). On the other hand, no study to date compared RG and its time course between smoothly moving targets or similar dynamic events presented with apparent motion. As such, the present experiment aimed, in part, to fill-in this gap while, simultaneously, attempting to explore if motion signal strength could account for discrepancy in the outcomes reported by Nagai and collaborators (2002) and those by De Sá Teixeira and collaborators (De Sá Teixeira & Hecht, 2014; De Sá Teixeira, 2014; De Sá Teixeira et al, 2016).

Participants were required to perform a spatial localization task, by displacing a cursor with a trackball to the location where a target vanished after an imposed retention interval, both while upright and while lying horizontal on their side (left lateral decubitus). Target could be shown moving smoothly or undergoing apparent motion.

Methods

Participants

Thirty-six right-handed participants, with ages between 18 to 57 (M = 23.46; SD = 8.96), volunteered for the experiment in exchange of partial course credits. All participants had normal or corrected to normal vision, no known neurological or vestibular deficits and were unaware of the purposes of the task. Before the experiment, each participant provided his/her written informed consent and all procedures were preapproved by the ethics committee of the University of Aveiro (protocol 34-CED/2021).

Stimuli and apparatus

A set of animations was used as stimuli. Each animation portrayed a white circle (target) with a diameter of 20 pixels (about 0.6º of visual angle), moving either vertically or horizontally at a constant speed of 600 pixels per second (px/s; about 14º/s) on an otherwise black background. Depending on the motion signal strength condition, target's position was updated every screen refresh (set at 60Hz), henceforth referred to as the *smooth motion* condition, or once every 200 ms (with the target being visible during 100 ms), referred to as the *apparent motion* condition. In each animation, the target emerged from the top, bottom, right or left side of the visible circular area of the screen (see below) and disappeared at a random location within an area of 100 × 100 pixels beyond the center of the screen and after covering a distance of 600 pixels. A black circular cursor, with a white border, appeared on the center of the screen 0, 150, 300, 450 or 600 ms after target's offset.

Stimuli was presented on a flat screen, with a resolution of 1080 × 1024 pixels (physical size of 37.5 × 29.9 cm). Participants' view was restricted to a circular window, with a diameter of 29.9 cm centered on the screen, with a custom-made cardboard cylinder, which ensured that no peripheral visual cues from the laboratory room were visible while also keeping their heads roughly at 50 cm from the screen. The experimental tasks were programmed in Python using PsychoPy (Peirce, 2007, 2009) and ran on a personal computer equipped with an external trackball with which the position of a cursor on the screen could be adjusted.

Procedure and design

The basic task consisted on a standard spatial localization. Each trial started with a white plus sign in the center of the screen, for 800 ms and, after a 200 ms blank screen, a randomly chosen animation was shown. After an imposed retention interval of 0, 150, 300, 450 or 600 ms, the cursor appeared. Participants had to adjust the location of the cursor to the position on the screen where the target was last seen (its offset location), as precisely as possible, using the provided trackball, confirming their response by the left button of the trackball. The next trial started immediately afterwards.

Each participant performed the spatial localization task four times in total, varying the strength of the motion signal (apparent or smooth motion) and their body posture (upright or left lateral decubitus). In order to facilitate the preparation of the apparatus in each experimental session, half of the participants performed first the smooth and apparent motion conditions (counterbalanced across participants) while upright and the other half the same conditions while on a decubitus posture. In the upright condition, participants sat on a chair which height could be adjusted so that their heads were inside the opening of the cardboard cylinder. In the decubitus condition, participants lay down on their left side on a plastic mattress, with their heads supported by a pillow such that their heads were also inside the opening of the cylinder. In both cases, the trackball was positioned horizontally and comfortable within reach of the participants' right hand (either on participants laps or on the mattress, for the upright condition, or on the mattress, for the decubitus condition; see Figure 1). Before initiating the experiment, each participant was allowed to practice the task until they felt comfortable with the trackball and stimuli.

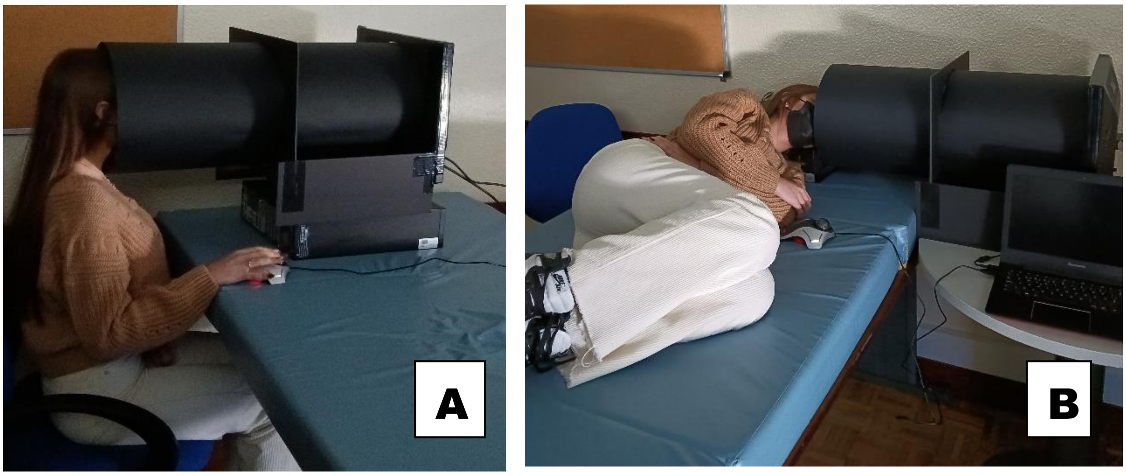

Figure 1 – Representation of the apparatus for the upright condition (Panel A) and for the decubitus condition (Panel B).

The experiment thus obeyed a repeated measures design given by 2 (posture: upright/decubitus [blocked]) × 2 (strength of the motion signal: smooth/apparent motion [blocked]) × 4 (motion trajectory: upward, downward, leftward, rightward) × 5 (retention time: 0, 150, 300, 450, 600ms) with 10 repetitions, amounting 800 trials. The whole experiment session lasted about 1 hour and 30 minutes.

Results

The arithmetic difference between the onscreen horizontal and vertical coordinates of the localization responses and the actual offset location was calculated for each trial and participant. Figure 2 depicts the mean spatial localization errors, in relation to the actual offset (origin of the plot) for each motion direction and retention interval (datapoints' color) for the smooth (top panels) and apparent (bottom panels) motion conditions and for the upright (leftward panels) and decubitus (rightward panels) conditions (see picture insets, where *G* and *I* arrows indicate, respectively, the direction of the physical gravity and idiotropic directions). Overall, it can be seen that apparent motion resulted in slightly bigger localization errors forward in the direction of target's motion and, for both conditions, those errors increased with retention interval (at least until 300 ms). For both motion conditions, bigger errors were found for target's moving 'downward' towards the participants' feet, irrespective of their positioning relative to gravity's direction. Albeit not as discernible, the same trend can be seen for errors orthogonal to target's trajectory for horizontally/vertically moving targets in the upright/decubitus conditions. These trends were all found to be supported by statistical evidence, as discussed in what follows.

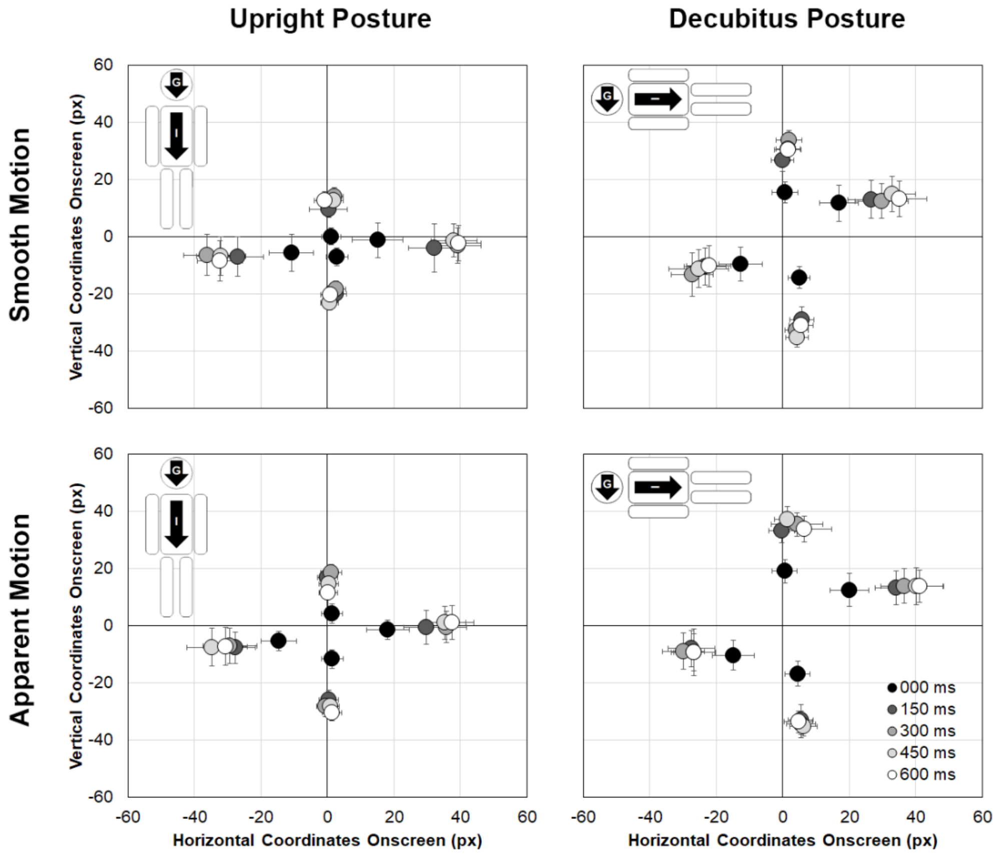

Figure 2 – Horizontal and vertical onscreen mean spatial localization errors as a function of target's motion direction and retention interval (datapoints) for smooth (top panels) and apparent (bottom panels) motion and the upright (left panels) and decubitus postures (right panels). Panel insets depict the body position, relative to the display with *G* and *I* arrows standing, respectively, for the direction of physical gravity and the idiotropic vector. Error bars depict the standard error for the means.

For statistical data analyses, the spatial localization errors were converted to M-displacements – localization errors along the target's trajectory – and O-displacements – localization errors orthogonal to the target's trajectory. Notice that positive/negative M-displacements reflect forward/backward errors in relation to target's offset and motion direction. As for O-displacement, negative values reflect a 'downward' error for horizontally moving targets but a leftward error for vertically moving targets.

Mean M-displacements (averaged across repetitions) were subjected to a repeated-measures ANOVA with motion signal strength, posture, motion direction and retention interval as independent variables. For this and the remainder statistical analyses, whenever the sphericity assumption was not met, degrees of freedom were subjected to the Greenhouse-Geisser correction. M-displacement was found to increase with retention interval, $F(1.648, 57.682) = 79.259$, $p < 0.01$, partial $\eta^2 = 0.694$, with no interaction with posture, $F(2.919, 102.158) = 0.191$, $p = 0.898$, partial $\eta^2 = 0.005$, or strength of motion signal, $F(3.087, 108.029) = 0.583$, $p = 0.632$, partial $\eta^2 = 0.016$. Post-hoc analyses revealed further that M-displacement increased with time up until 300 ms, stabilizing for longer durations. Direction was also found to have a significant effect on M-displacements, $F(2.49, 87.148) = 12.390$, $p < 0.01$, partial $\eta^2 = 0.261$, and to significantly interact with posture, $F(3, 105) = 19.649$, $p < 0.01$, partial $\eta^2 = 0.360$. These results reflect the fact that M-displacements were bigger for downward, as compared with upward, motion directions for the upright condition, but bigger for rightward, as compared with leftward motion directions, for the decubitus condition. Stated differently, there was a systematic trend for bigger M-displacements for targets moving towards the participants' feet (along their idiotropic vector), irrespective of the direction of physical gravity. Figure 3 shows polar plots for mean M-displacements (radius) as a function of motion direction onscreen (angle) and retention interval (line parameter) for smooth (panels A and B) and apparent motion (panels C and D) and the upright (panels A and C) and decubitus (panels B and D) conditions. It can be seen that the data conforms closely to a quadrilateral shape distorted towards the idiotropic vector. Furthermore, M-displacements tend to increase with time for targets moving orthogonally to the participants' body and towards participants' feet, but to decrease with time for target's moving towards the participants' heads, as revealed with a significant interaction between motion direction and retention, $F(7.745, 271.062) = 3.453$, $p = 0.001$, partial $\eta^2 = 0.090$, and a three-way interaction between posture, motion direction and retention interval, $F(7.353, 257.364) = 2.659$, $p =$

0.01, partial $\eta^2 = 0.071$. Importantly, and albeit motion signal strength does not result in a significant main effect, $F(1, 35) = 2.420$, $p = 0.129$, partial $\eta^2 = 0.065$, it does significantly magnify the interaction between body posture and motion direction, $F(3, 105) = 4.561$, $p = 0.005$, partial $\eta^2 = 0.115$. That is, the trend for bigger M-displacements for targets moving towards participants' feet is further increased for apparent in comparison with smooth motion targets. In fact, a significant main effect for body posture, $F(1, 35) = 9.774$, $p = 0.004$, partial $\eta^2 = 0.218$, disclosures that M-displacement was, in general, bigger for the decubitus conditions, in comparison with the upright posture. No other main effect or interaction reached statistical significance.

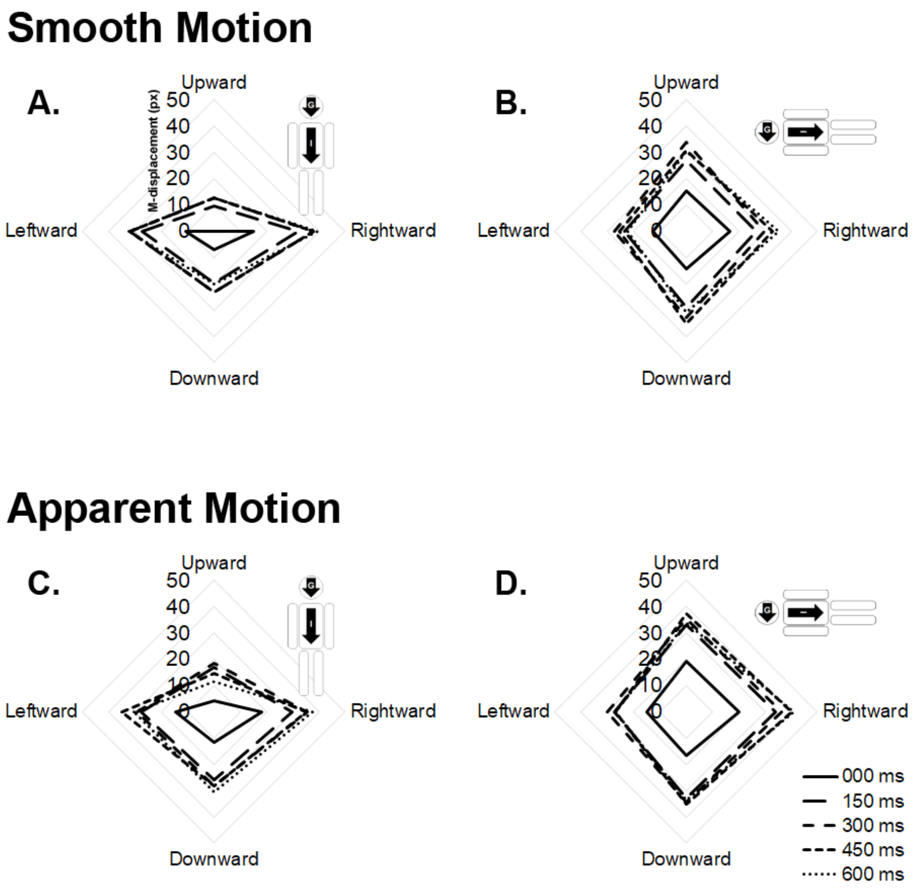

Figure 3 – Polar plots for mean M-displacements (radius) as a function of target's motion direction (angle) and retention interval (line parameter) for smooth (panels A and B) and apparent (panels C and D) motions. Leftward panels (A and C) are for the upright and rightward panels (B and D) for the decubitus body posture (see insets depicting the direction of physical gravity – *G* – and the idiotropic vector – *I*).

In what refers to O-displacement, statistically significant main effects were found for both posture, $F(1, 35) = 5.120$, $p = 0.030$, partial $\eta^2 = 0.128$, and target's motion direction, $F(3, 105) = 34.792$, $p < 0.01$, partial $\eta^2 = 0.499$, with a significant interaction between those same factors, $F(3, 105) = 25.829$, $p < 0.01$, partial $\eta^2 = 0.425$. Taken together, these results reflect the fact that participants made bigger errors towards their feet for horizontally or vertically moving targets when in an upright or decubitus position, respectively. Furthermore, when in a decubitus posture, there was a trend for targets moving 'downward' toward participants' feet to be mislocalized to their right but to their left for targets moving 'upward' towards their heads. No other main effects or interactions were found for O-displacement values.

Discussion and Conclusion

Representational Gravity has been defined, in the relevant literature, as a displacement of the perceived offset location of a moving object 'downward in the direction of gravity' (Hubbard, 2005). Given the multisensorial nature of the perceived vertical direction, the term 'downward' in that definition is ill-defined and might, potentially, be determined by the sensed direction of physical gravity, via vestibular signals, the direction of the body's longitudinal axis (idiotropic vector) or a combination of both. Previous inquiries into this issue found either evidence for an idiotropic dominance – that is, Representational Gravity seems to be determined solely by the idiotropic vector (De Sá Teixeira & Hecht, 2014; De Sá Teixeira, 2014; De Sá Teixeira et al, 2016) – or vestibular dominance – with spatial localization errors being bigger for target's moving toward the physical gravitational pull, irrespective of the observer's posture (Nagai et al., 2002). As both results emerged for disparate features of the dynamic stimuli (smooth motion *versus* apparent motion) and response modality (spatial localization with a mouse *versus* judgements concerning a mnesic probe), the different outcomes might be due to one or both of those differences. As such, the present study was designed to clarify if the strength of the motion signal, known to modulate the magnitude of Representational Momentum and to interact with response modality (Kerzel, 2003), could account for the discrepancy.

Results were compatible with idiotropic dominance, with the direction of Representational Gravity (both when indexed with M-displacement and O-displacement) following body position, not physical gravity. Importantly, this trend was found for both smoothly moving objects and apparent motion displays, revealing that this factor cannot account for the discrepancy in the relevant literature. Besides dynamic features of the display (smooth *versus* apparent motion), one other conspicuous difference between the study by Nagai and collaborators (2002) and the ones by De Sá Teixeira and collaborators (De Sá Teixeira & Hecht, 2014; De Sá Teixeira, 2014; De Sá Teixeira et al, 2016) refers to response modality – in fact, it has been reported that the magnitude of Representational Gravity is increased for judgements of a probe in comparison with mouse localizations (De Sá Teixeira et al., 2019). It is also worth referring that while in the present study all target's motions were confined to the frontoparallel plane, with participants posture varying between the upright and decubitus, in Nagai and collaborators (2002) the targets always moved parallel to the participant's idiotropic vector, with their posture varying between the upright and the prone postures (experiment 1). The degree to which either of these factors could explain the different conclusions still awaits empirical inquiries. Notwithstanding, and for the sake of completeness, in the present study we will hypothesize on possible accounts for the discrepancy, beyond mere methodological considerations, venturing into perceptual/cognitive based explanations. In our study, care was taken to completely remove any visual orientation cue, both in the form of peripheral cues from the laboratorial environment and from the visual display, constraining the view of the screen to a circular window. The study by Nagai and collaborators (2002) was performed in a dark room although the stimuli were presented in a screen with a white background, which could illuminate, even if only faintly, visual cues from the laboratory context. Even if that was not the case, the screen itself was shown as a rectangular frame. Although the interaction between vestibular/somatosensory cues and orientation of the visual context is still to be explored, the latter has been recently found to impact on spatial localizations (Freitas & De Sá Teixeira, 2021). It might be the case that in the study by Nagai and collaborators (2002) dimly lit features or the frame of the screen, acting as visual orientation cues, led to the results, not vestibular signals per se. On the other hand, the literature on field-dependence/independence – that is, the degree to which people are influenced by the context of their surroundings – has put forth evidence for inter-cultural differences (Bagley, 1995; Ji et al., 2000; Kühnen et al., 2001), with oriental participants (as those who participated in the study by Nagai et al., 2002) being more susceptible to integrate contextual features into their perceptual judgements than occidental observers (as the ones in the present study and those conducted by De Sá Teixeira and collaborators). Albeit this difference is unlikely to be the sole explaining factor, if it even contributes to this discrepancy, it might be worth to be explored in future studies.

In the present study, we also replicated the usually found trend for Representational Momentum to increase with time up until about 300 ms (Freyd & Johnson, 1987; Kerzel, 2000) and more so for ‘descending’ in comparison with ‘ascending’ targets (relative to the idiotropic vector; De Sá Teixeira et al., 2013; De Sá Teixeira, 2016a). However, we did not fully replicate the results reported by De Sá Teixeira and collaborators (2013; see also, De Sá Teixeira et al., 2019), where O-displacement for horizontally moving targets increases downward with increasing temporal intervals. Likewise, we failed to found evidence for a null temporal course for Representational Gravity in those conditions where the idiotropic vector is in conflict with the physical gravitational pull (De Sá Teixeira & Hecht, 2014; De Sá Teixeira, 2014; De Sá Teixeira et al, 2016). On this respect, it is valuable to note that in the present study, the target was shown moving at a somewhat faster speed than any of those previous reports. With speed being a prominent feature in determining Representational Momentum, and given its known reciprocal relation with Representational Gravity (which emerges once Representational Momentum ceases to evolve; De Sá Teixeira et al., 2013; see also De Sá Teixeira et al, 2019), it is likely that target’s velocity interfered with those usually found trends. What is more, Representational Gravity is known to increase with retention intervals far beyond the 600 ms (the maximum used in the present study), up until at least 1400ms (De Sá Teixeira, 2016b). Finally, the present results also disclosed bigger Representational Momentum effects for targets undergoing apparent, as opposed to smooth, motion, further replicating previously reported trends (Kerzel, 2003).

As a concluding remark, the present study and the disclosed outcomes reveal the multidimensional nature of these phenomena, simultaneously indexing perceptual, somatosensory, vestibular and cognitive factors, highlighting its potential role in uncovering previously unsuspecting multisensorial effects.

References

Angelaki, D. E., Klier, E. M., & Snyder, L. H. (2009). A vestibular sensation: probabilistic approaches to spatial perception. *Neuron, 64*(4), 448-461. https://doi.org/10.1016/j.neuron.2009.11.010

Aubert, H. (1861). Eine scheinbare bedeutende Drehung von Objecten bei Neigung des Kopfes nach rechts oder links. *Archiv für pathologische Anatomie und Physiologie und für klinische Medicin*, *20*(3), 381-393. https://doi.org/10.1007/BF02355256

Bagley, C. (1995). Field independence in children in group-oriented cultures: Comparisons from China, Japan, and North America. *The Journal of Social Psychology, 135*, 523–525. https://doi.org/cpzqsf

Clément, G., & Reschke, M. F. (2008). Spatial orientation. In *Neuroscience in Space* (pp. 189-232). Springer, New York, NY.

De Sá Teixeira, N. A. (2014). Fourier decomposition of spatial localization errors reveals an idiotropic dominance of an internal model of gravity. *Vision Research, 105*, 177–188. https://doi.org/10.1016/j.visres.2014.10.024

De Sá Teixeira, N. A. (2016). How fast do objects fall in visual memory? Uncovering the temporal and spatial features of representational gravity. *PLOS ONE, 11*(2), e0148953. https://doi.org/10.1371/journal.pone.0148953

De Sá Teixeira, N. A. (2016a). The visual representations of motion and of gravity are functionally independent: Evidence of a differential effect of smooth pursuit eye movements. *Experimental Brain Research, 234*(9), 2491-2504. https://doi.org/10.1007/s00221-016-4654-0

De Sá Teixeira, N. A., & Hecht, H. (2014). The dynamic representation of gravity is suspended when the idiotropic vector is misaligned with gravity. *Journal of Vestibular Research*, *24*(4), 267-279. DOI:10.3233/VES-140511

De Sá Teixeira, N. A., Hecht, H., & Oliveira, A. M. (2013). The representational dynamics of remembered projectile locations. *Journal of Experimental Psychology: Human Perception and Performance, 39*(6), 1690–1699. https://doi.org/10.1037/a0031777

De Sá Teixeira, N. A., Hecht, H., Artiles, A. D., Seyedmadani, K., Sherwood, D. P., & Young, L. R. (2016). Vestibular stimulation interferes with the dynamics of an internal representation of 280 gravity. *QJ Exp Psychol, 218,* 1-16.

De Sá Teixeira, N. A., Kerzel, D., Hecht, H., & Lacquaniti, F. (2019). A novel dissociation between representational momentum and representational gravity through response modality. *Psychological Research, 83*(6), 1223–1236. https://doi.org/10.1007/s00426-017-0949-4

De Vrijer, M., Medendorp, W. P., & Van Gisbergen, J. A. M. (2008). Shared computational mechanism for tilt compensation accounts for biased verticality percepts in motion and pattern vision. *Journal of neurophysiology*, *99*(2), 915-930. https://doi.org/10.1152/jn.00921.2007

De Vrijer, M., Medendorp, W. P., & Van Gisbergen, J. A. M. (2009). Accuracy-precision trade-off in visual orientation constancy. *Journal of vision*, *9*(2), 9-9. https://doi.org/10.1167/9.2.9

Freitas, R. R., & De Sá Teixeira, N. A. (2021). Visual space orientation and representational gravity: Contextual orientation visual cues modulate the perceptual extrapolation of motion. *Journal of Experimental Psychology: Human Perception and Performance, 47*(12), 1647–1658. https://doi.org/10.1037/xhp0000962

Freyd, J. J., & Finke, R. A. (1984). Representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *10*(1), 126–132. https://doi.org/10.1037/0278-7393.10.1.126

Freyd, J. J., & Finke, R. A. (1985). A velocity effect for representational momentum. *Bulletin of the Psychonomic Society, 23*(6), 443–446. https://doi.org/10.3758/BF03329847

Freyd, J.J., & Johnson, J.Q. (1987). Probing the time course of representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *13*, 259–269. DOI: 10.1037//0278-7393.13.2.259

Glasauer, S., & Mittelstaedt, H. (1992). Determinants of orientation in microgravity. *Acta Astronautica*, *27*, 1-9. https://doi.org/10.1016/0094-5765(92)90167-H

Hubbard, T. L. (1990). Cognitive representation of linear motion: Possible direction and gravity effects in judged displacement. *Memory & Cognition, 18,* 299-309. https://doi.org/10.3758/BF03213883

Hubbard, T. L. (2005). Representational momentum and related displacements in spatial memory: A review of the findings. *Psychonomic bulletin & review*, *12*(5), 822-851. https://doi.org/10.3758/BF03196775

Hubbard, T. L. (2020). Representational gravity: Empirical findings and theoretical implications. *Psychonomic Bulletin & Review, 27*(1), 36-55. https://doi.org/10.3758/s13423-019-01660-3

Hubbard, T. L.. & Bharucha, J. J. (1988). Judged displacement in apparent vertical and horizontal motion. *Perception & Psychophysics, 44*, 211-221. https://doi.org/10.3758/BF03206290

Hubbard, T. L. (1990). Cognitive representation of linear motion: Possible direction and gravity effects in judged displacement. *Memory & Cognition, 18*(3), 299–309. https://doi.org/10.3758/BF03213883

Ji, L. J., Peng, K., & Nisbett, R. E. (2000). Culture, control, and perception of relationships in the environment. *Journal of Personality and Social Psychology, 78*(5), 943–955. https://doi.org/10.1037/0022-3514.78.5.943

Kelly, M. H., & Freyd, J. J. (1987). Explorations of representational momentum. *Cognitive Psychology*, *19*(3), 369-401. https://doi.org/10.1016/0010-0285(87)90009-0

Kerzel, D. (2000). Eye movements and visible persistence explain the mislocalization of the final position of a moving target. *Vision Research, 40*(27), 3703-3715. https://doi.org/10.1016/S0042-6989(00)00226-1

Kerzel, D. (2002). A matter of design: No representational momentum without predictability. *Visual Cognition*, *9*(1-2), 66-80. https://doi.org/10.1080/13506280143000322

Kerzel, D. (2003). Mental extrapolation of target position is strongest with weak motion signals and motor responses. *Vision Research, 43*(25), 2623-2635. https://doi.org/10.1016/S0042-6989(03)00466-8

Kerzel, D. (2003a). Attention maintains mental extrapolation of target position: Irrelevant distractors eliminate forward displacement after implied motion. *Cognition*, *88*(1), 109-131. https://doi.org/10.1016/S0010-0277(03)00018-0

Kerzel, D. (2003b). Centripetal force draws the eyes, not memory of the target, toward the center. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29*(3), 458–466. https://doi.org/10.1037/0278-7393.29.3.458

Kerzel, D., Jordan, J. S., & Müsseler, J. (2001). The role of perception in the mislocalization of the final position of a moving target. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(4), 829–840. https://doi.org/10.1037/0096-1523.27.4.829

Kühnen, U., Hannover, B., Roeder, U., Shah, A. A., Schubert, B., Upmeyer, A., & Zakaria, S. (2001). Cross-cultural variations in identifying embedded figures: Comparisons from the United States, Germany, Russia, and Malaysia. *Journal of Cross-Cultural Psychology*, *32*(3), 366-372. https://doi.org/10.1177/0022022101032003007

Lacquaniti, F., Bosco, G., Indovina, I., La Scaleia, B., Maffei, V., Moscatelli, A., & Zago, M. (2013). Visual gravitational motion and the vestibular system in humans. *Frontiers in Integrative Neuroscience*, *7*, 101. https://doi.org/10.3389/fnint.2013.00101

MacNeilage, P. R., Ganesan, N., & Angelaki, D. E. (2008). Computational approaches to spatial orientation: from transfer functions to dynamic Bayesian inference. *Journal of neurophysiology*, *100*(6), 2981-2996. https://doi.org/10.1152/jn.90677.2008

Mars, F., Popov, K., & Vercher, J. L. (2001). Supramodal effects of galvanic vestibular stimulation on the subjective vertical. *Neuroreport*, *12*(13), 2991-2994. doi: 10.1097/00001756-200109170-00047

Mittelstaedt, H. (1983). A new solution to the problem of the subjective vertical. *Naturwissenschaften*, *70*(6), 272-281. https://doi.org/10.1007/BF00404833

Mittelstaedt, H. (1986). The subjective vertical as a function of visual and extraretinal cues. *Acta psychologica*, *63*(1), 63-85. https://doi.org/10.1016/0001-6918(86)90043-0

Müsseler, J., Stork, S., & Kerzel, D. (2002). Comparing mislocalizations with moving stimuli: The Fröhlich effect, the flash-lag, and representational momentum. *Visual Cognition*, *9*(1-2), 120-138. https://doi.org/10.1080/13506280143000359

Nagai, M., Kazai, K., & Yagi, A. (2002). Larger forward memory displacement in the direction of gravity. *Visual Cognition, 9*, 28–40. https://doi.org/10.1080/13506280143000304

Nijhawan, R. (2008). Visual prediction: Psychophysics and neurophysiology of compensation for time delays. *Behavioral and Brain Sciences, 31*(2), 179-198. doi:10.1017/S0140525X08003804

Oman, C. M. (2003). Human visual orientation in weightlessness. *Levels of perception*, 375-398.

Peirce, J. W. (2007). PsychoPy – psychophysics software in python. *Journal of Neuroscience Methods*, *162,* 8-13.

Peirce, J. W. (2009). Generating stimuli for neuroscience using PsychoPy. *Frontiers in Neuroinformatics, 2,* 10.

Reed, C. L., & Vinson, N. G. (1996). Conceptual effects on representational momentum. *Journal of Experimental Psychology: Human Perception and Performance, 22*(4), 839–850. https://doi.org/10.1037/0096-1523.22.4.839

Zupan, L. H., Merfeld, D. M., & Darlot, C. (2002). Using sensory weighting to model the influence of canal, otolith and visual cues on spatial orientation and eye movements. *Biological cybernetics*, *86*(3), 209-230. https://doi.org/10.1007/s00422-001-0290-1