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BEATRIZ DA GRAÇA SILVA VELADO

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IMPACTO DA GRAVIDADE NAS ASSIMETRIAS DE BUSCA VISUAL: GRAVIDADE INTERNA COMO CARATERÍSTICA VISUAL OU EVENTO FAMILIAR DINÂMICO?

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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 à minha avó Lurdes.

o júri

presidente

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agradecimentos

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palavras-chave

Perceção de Movimento, Perceção de Evento; Modelo Interno da Gravidade; Busca Visual; Assimetria de Busca.

resumo

Diversas linhas de pesquisa convergentes têm apoiado a ideia de que determinados processos neurais especializados produzem informações a priori sobre os efeitos esperados da gravidade para adaptar as respostas motoras e percetivas a eventos dinâmicos. Este suposto modelo interno da gravidade pode modular a eficiência na busca visual por sujeitos que apresentam, ou não, movimentos gravitacionalmente coerentes. No presente trabalho, exploramos essa possibilidade através de uma tarefa de busca visual, envolvendo conjuntos de 2 a 8 objetos movendo-se para a frente e para trás. O alvo poderia ser um objeto com um padrão de aceleração/desaceleração, entre distratores movendo-se a uma velocidade constante ou o contrário. Para além disso, a direção da força gravitacional, conforme indicada pelos padrões de movimento de aceleração/desaceleração, poderia estar alinhada ou desalinhada com a gravidade da Terra. No geral, as buscas por alvos com padrão de aceleração/desaceleração foram mais eficientes do que aquelas com alvos com velocidade constante, exceto, visivelmente, quando os estímulos eram congruentes com a força gravitacional da Terra, caso em que a assimetria na busca visual desaparecia. Os resultados são interpretados como reflexo da contribuição conjunta e mutuamente eliminadora da deteção de baixo nível dos padrões de aceleração e da deteção de nível mais alto de violações inesperadas do movimento gravitacional.

keywords

Motion Perception, Event Perception, Internal Model of Gravity, Visual Search, Search Asymmetry.

abstract

A wealth of converging research lines has led support to the notion that specialized neural processes output aprioristic information about the expected effects of gravity to fine-tune motor and perceptual responses to dynamic events. Arguably, this putative internal model of gravity might modulate the efficiency in visual search for objects conforming or not to gravitationally coherent dynamics. In the present work, we explored this possibility with a visual search task involving arrays of 2 to 8 objects moving back-and-forth. The target could be a bouncing object with distractors moving periodically at a constant speed or the reverse. Moreover, the direction of the gravitational pull, as implied by the bouncing motion patterns, could be aligned or misaligned with Earth's gravity. Overall, searches for bouncing targets were more efficient than periodic ones except, notoriously, when stimuli displays were congruent with Earth's gravitational pull, in which case the visual search asymmetry disappeared. Outcomes are interpreted as reflecting the joint and mutually cancelling contribution of low-level detection of acceleration patterns and higher-level detection of unexpected violations of gravitational motion.

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Introduction

The processing capabilities of the human visual system can and have been probed by exploring its efficiency when seeking out an object or item, among distractors, with the implementation of Visual Search tasks (Wolfe, 2018). Albeit several aspects of visual processing and spatial attention came to be better understood, visual search capabilities for moving objects, particularly when undergoing complex dynamics such as acceleration, has seldom been investigated (but see Nakada & Murakami, 2022). This is all the more surprising for, in our ecological environment, we are routinely faced and have to interact with a dynamic world, continuously and unescapably ruled by physical invariants such as, prominently, Earth's gravitational pull. In fact, it has been increasingly recognized that *Internal Models of Gravity* affect and are taken into account by our visual system, in order to improve visual motion anticipation and to fine-tune hand interception tasks (Hecht et al., 1996; Indovina et al., 2005; Lacquaniti et al., 2013; McIntyre et al., 2001; Zago & Lacquaniti, 2005a; for a review see Delle Monache et al., 2021), particularly when the motion pattern conforms to gravitational acceleration (Brouwer et al., 2006; Delle Monache et al., 2019; Jörges & López-Moliner, 2017; Lacquaniti et al., 2013; McIntyre et al., 2001; Zago & Lacquaniti, 2005a, b; Zago et al., 2008, 2009). The present study aims to further explore how such putative internal models of gravity aid and/or guide visual search within a dynamic context and, in particular, if visual gravitational motion acts as a visual feature, prone for detection in a visual search task, or if it outputs expected dynamics improving visual search efficiency through easier detection of local variations of gravitationally congruent motion.

Visual Search

Visual search tasks have been widely recognized as a valuable instrument for studying attention and visual perception, ever since they were introduced in the seminal article authored by Treisman and Gelade (1980). In a visual search task, participants are required to seek out a specific target object amongst a set of distractors and their performance measured through response times and detection accuracy (Wolfe, 1998, 2001, 2018), often complemented with eye tracking measures (Greene & Rayner, 2001; Kowler, 2011; Najemnik & Geisler, 2008; Rao et al., 2002; Williams, 1966). Originally (Treisman & Gelade, 1980), search tasks were developed to test specific predictions of the Feature Integration Theory (FIT; see Kristjánsson, 2015, for a critical overview). According to FIT a first stage in visual perception consists on the modular processing of simple features, preattentively and carried out in parallel by dedicated and neurophysiologically segregated structures. Computationally, each processing module would output its own feature map, signalling the presence of those simple features (e.g., colour, orientation, motion, spatial frequency, etc.) for which it was attuned and simultaneously across the entire visual field. Through attentional processes, carried out in a serial fashion, and so as to account for visual consciousness, those simple features could be locally bind together. This latter stage would act on a general spatial or object map and would require the expenditure of attentional resources (Rosenholtz, 2001; Royden el al., 2001; Takeuchi, 1997; Treisman & Souther, 1985; Verghese, 2001). In a visual search task, FIT predicts, among others (Treisman, 1988; Treisman & Gelade, 1980; Treisman & Gormican, 1988; Treisman & Paterson, 1984; Treisman & Souther, 1985), that (i) targets defined only by simple features (e.g., detect a blue object among green and brown distractors) would pop-out and be easily detected, regardless of the number of distractors; (ii) targets defined by the conjunction of two or more simple features (e.g., detect a green T letter among brown T letters and green X letters) could only be detected by performing a serial item-by-item search, locally binding simple features (T shape and green colour), resulting in search times that increase linearly with the number of items presented; (iii) the detection of the presence of a simple feature would be far easier than the detection of its absence, since feature maps respond only in the former case. The latter prediction, aptly coined Visual Search Asymmetries, refers to the difference in effectiveness with which a specific target object can be found within a set of distractors compared to the reverse scenario (Shen & Reingold, 2001; Treisman & Souther, 1985; Wolfe, 2018).

Treisman's FIT and the visual search task inspired a wealth of research which, expectedly, resulted in further theoretical elaborations and novel empirical observations. For one, the idea that the slope of the linear functions relating response times to the number of onscreen items could be used to diagnose the serial (positive slope) or parallel (null slope) nature of the underlying mental or neural processes – an insight borrowed from early work by Sternberg (1969) – was revised and currently interpreted more in terms of search efficiency (varying continuously from highly efficient to highly inefficient visual searches; Rosenholtz, 2001; Royden et al., 2001; Takeuchi, 1997; Treisman & Paterson, 1984; Treisman & Souther, 1985; Verghese, 2001), with no presumption about the underlying mechanisms (see, e.g., Moore & Wolfe, 2001; Townsend, 1990; Wolfe, 2018). Likewise, and under the notion of Guided Search (Wolfe et al., 1989), the role of strategic top-down attentional processes was recognized in visual search, be it in terms of actively employing simple features to guide visual search (e.g., ignoring all green objects to more efficiently search for the brown rectangle) or taking advantage of explicit knowledge (e.g., search for a traffic light above a road intersection) (Wolfe et al., 1989, Wolfe, 2001, 2018). Finally, and specifically in what concerns Asymmetries in Visual Search, it soon became clear that identifying and establishing what is a simple feature, the detection of which is easier than its absence, is far more challenging than originally assumed (Wolfe, 2001). For example, it is easier to find a "bump" among ellipses than an ellipse among "bumps" (Kristjánsson & Tse, 2001); it is easier to find an inverted silhouette of an elephant among upright ones than the reverse (Wolfe, 2001); finally, it is easier to find mirrored letters among 'normal' letters than the reverse (Frith, 1974; Reicher et al., 1976). In these and similar cases, it is hard to identify exactly what "simple feature" might account for these asymmetries (Wang et al, 1994; Wolfe, 2001). Notwithstanding, those same outcomes can be readily interpreted in terms of familiarity being used to guide visual attention, with non-familiar or novel items being easier to find (Flowers & Lohr, 1985; Frith, 1974; Lubow & Kaplan, 1997; Malinowski & Hübner, 2001; Richards & Reicher, 1978; Wang et al, 1994), either because familiar distractors group better than novel items, facilitating target detection (Karni & Sagi, 1991), or because 'novelty' is itself a pre-attentive feature (albeit slightly weaker as such in comparison with other simple features; Wang et al., 1994; Malinowski & Hübner, 2001).

Expectedly, several authors used Visual Search tasks, in general, and found Visual Search Asymmetries, in particular, to explore features of visual motion processing. For starters, a moving target among stationary distractors has been consistently found to be very efficiently detected, unlike a stationary target among moving distractors (McLeod et al., 1988; Verghese & Pelli, 1992), except, notoriously, when the moving distractors conform to a structured visual flow congruent with a forward motion of the observer (Royden et al., 2001). Similarly, a fast-moving target among slow-moving distractors is found more efficiently than the reverse situation (Ivry & Cohen, 1992; Rosenholtz, 1999). Taken together, these reports strongly suggest that stronger motion signals, particularly faster moving objects, are easier to detect than weaker motion signals. Furthermore, familiarity/novelty seems also to modulate visual search asymmetries involving moving targets/distractors. Howard and Holcombe (2010) report that unexpected changes in the direction of motion of gratings was easier to detect and, overall, was efficient in attracting attention. In a similar vein, Nakada and Murakami (2022) recently reported a visual search asymmetry in which a target given by a moving Gabor grating changing directions was easier to find among constantly drifting distractors than the reverse. Of particular relevance, Nakayama and Motoyoshi (2017; experiment 3) further report that an accelerated target is easier to find among distractors moving at constant speeds, providing further support for their argument that the visual system is directly sensitive to accelerations, albeit solely at a pre-attentive level.

Internal Model of Gravity

Beyond early processing of visual motion (Nakayama & Motoyoshi, 2017), human observers have been found to be remarkably inaccurate at estimating objects' accelerations (Gottsdanker, 1956; Jörges & López-Moliner, 2017; Lacquaniti et al., 2013; McIntyre et al., 2001; Snowden et al., 1991; Watamaniuk and Duchon, 1992; Werkhoven et al., 1992; Zago et al., 2009), and as a result, do not effectively employ this information when engaging in manual interception tasks (Brouwer et al., 2002; Port et al. 1997).

Remarkably, however, this inability of the visual system vanishes when the motion pattern conforms to gravitational acceleration, both in visual perception and hand interception tasks (Hecht et al., 1996; Indovina et al., 2005; Lacquaniti et al., 2013; McIntyre et al., 2001; Zago & Lacquaniti, 2005a; but see, Baurès et al., 2007, for a critical view). These outcomes, along with a wealth of converging research lines (Bosco et al., 2008; Brouwer et al., 2006; Delle Monache et al., 2017; Jörges & López-Moliner, 2017; Lacquaniti et al., 2013; McIntyre et al., 2001; Zago & Lacquaniti, 2005a, b; Zago et al., 2008, 2009), has led support to the notion that specialized neural processes output aprioristic information about the expected effects of gravity in order to fine-tune motor and perceptual responses to dynamic events, in the form of an Internal Model of Gravity. In fact, Earth's gravity stands as a ubiquitous environmental invariant, constraining both the behaviour of animals and the kinematic patterns of inanimate objects in a similar fashion. As such, internally modelling its effects in order to more efficiently anticipate future states of dynamic events would certainly be highly adaptive both in terms of perceptual predictions as well as to support efficient motor (Lacquaniti et al., 2013; Miwa et al., 2019; Senot et al., 2005; Zago et al., 2008; Zago et al., 2009). A putative internal model of gravity would thus integrate expectations about the forces acting on an object (motion extrapolation plus anticipated effects of gravitational acceleration in terms of downward acceleration and upward deceleration), information from the vestibular system, visual orientation of polarized objects (e.g., other humans, trees, etc) and body orientation (Clément et al., 2013; Harris et al., 2014; Jörges & López-Moliner, 2017;

Lacquaniti et al., 2013; Miwa et al., 2019), outputting information to improve catching and hitting tasks (Senot et al., 2005; Tresilian, 1993), visual processing of trajectory estimation (Werkhoven et al., 1992), and spatial perception (Clément et al., 2008).

Arguably, the functioning of an internal model of gravity, such conceived, should also impact on the performance in visual search tasks, given targets/distractors being subjected to gravitationally coherent or incoherent motion patterns. The present study stands as a first exploration of this idea, further expanded upon in the next section.

The Present Study

In the present study, observers performed a series of visual search tasks involving small balls moving periodically back and forth either at a constant speed or in a bouncing pattern (accelerating toward one direction and, upon covering a fixed distance, bouncing back and decelerating toward the opposite direction). Within each block, the target, when present, could either be shown moving in a bouncing pattern (with distractors moving at a constant speed) or at a constant speed (among bouncing distractors). Furthermore, for whichever objects subjected to a bouncing pattern (target or distractors) the direction of the implied "gravitational" pull was varied: the balls could accelerate downward (and decelerate upwards), accelerate upwards (and decelerate downwards), accelerate leftwards (and decelerate rightwards) or accelerate rightwards (and decelerate leftwards). Finally, in each trial, the number of balls onscreen was systematically varied between 2 and 8.

Based upon the literature reviewed above, particularly in what refers to visual search asymmetries with moving stimuli, we hypothesized that, overall, bouncing targets (among constant speed distractors) would be more visually salient and, consequently, easier to find than targets moving at a constant speed (among bouncing distractors; see Nakayama & Motoyoshi, 2017). Predictions of an internal model of gravity would apply, specifically, to the condition where the bouncing motion pattern (either of the target or of the distractors) conformed to visual gravitational motion, that is, accelerating downwards and decelerating upwards. To the degree that gravitational acceleration is taken as a simple feature, within the logic put forth by Treisman (Treisman & Gelade, 1980), one would predict that the visual search asymmetry between bouncing and constant speed targets to be magnified. That is, it would be easier to detect the presence of gravitational acceleration, taken as a visual feature, in a bouncing target than its absence, in a target moving at a constant speed, and beyond the visual saliency produced by acceleration in general. On the other hand, to the degree that the output of a putative internal model of gravity is fed into expectations of visual motion, it could also be hypothesized that non-familiar (or, rather, not expected) constantly moving targets, when embedded within a context of distractors moving in accordance with gravity, would be easier to detect (in comparison with targets moving in an expected or familiar bouncing pattern; see Wang et al., 1994). In this case, the novelty/familiarity of visual gravitational motion would act in opposition to the visual saliency of acceleration patterns, either nulling those effects or even reversing them. Lastly, a scenario where visual search asymmetries between bouncing and constant speed balls is unchanged with the direction toward which the former accelerates (downwards, upwards, leftwards or rightwards) would imply that an internal model of gravity does not provides useful information for visual search (that is, a null scenario).

Methods

Participants

Fifty-five participants volunteered for the experiment in exchange for either course credits or a 5€ voucher. Their ages ranged between 18 and 55 years (*M* = 22.4; *SD* = 7.47), all had normal or corrected-to-normal vision and were unaware of the purposes of the experiment. Before performing the task, all participants provided written informed consent and all procedures were approved by the ethics committee of the University of Aveiro (Protocol 34-CED/2021).

Stimuli and apparatus

Stimuli displays consisted of a set of white circles (balls), with a diameter of 9 pixels (about 0.24º), moving back-and-forth, on an otherwise black background (see Figure 1, panel A). On each trial, the set of balls varied between a minimum of 2 and a maximum of 8 balls, occupying randomly chosen positions on a virtual circular grid around the centre of the screen, such that all balls were equidistant from the latter (about 8.5º from the centre of the screen; see Figure 1, panel B; notice that the areas depicted in the figure where not visible to the participants).

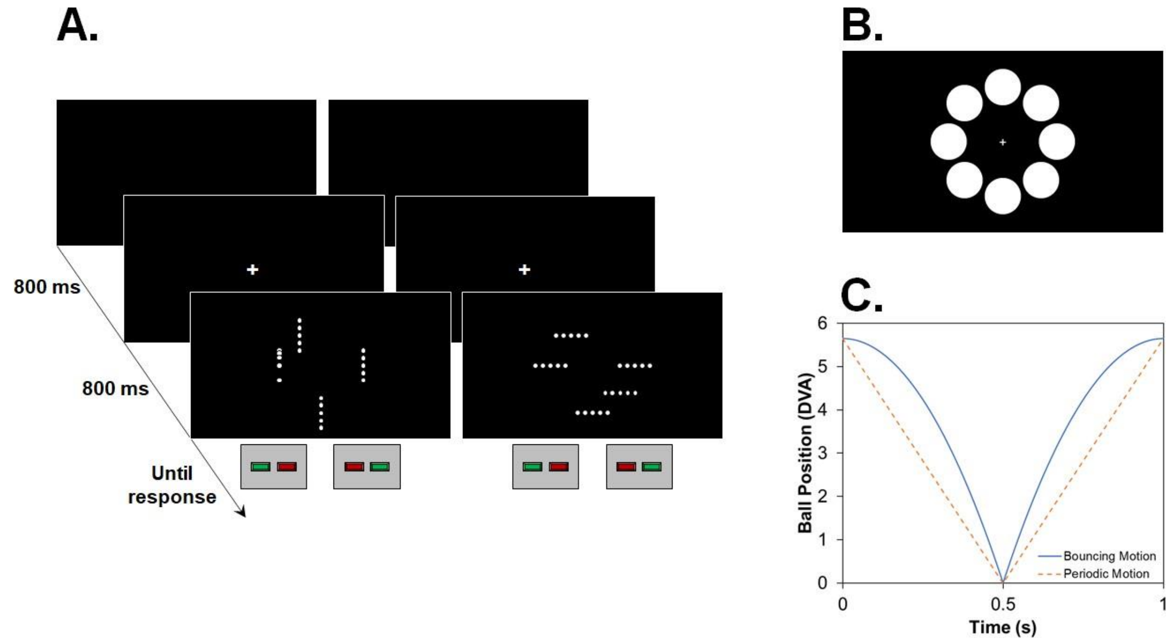
Two different motion patterns were possible for each ball – *bouncing* or *constant speed*. In the constant speed motion, the ball moved at a speed of about 0.24 pixels per second (0.006º/s), alternating directions after covering a length of 216 pixels (about 5.65º). In the bouncing motion pattern, the ball also moved along a length of 216 pixels, accelerating toward one direction (henceforth referred to as *G-direction*) and, when reaching the endpoint of its trajectory, decelerating toward the opposite direction until reaching a zero speed, after which it again accelerated toward the other direction (see Figure 1, panel C). The bouncing motion pattern was calculated so that, at the observers' distance, it corresponded to the optic image which would ensue from a ball with a diameter of 5.41 cm (slightly larger than Squash ball but slightly smaller than a Tennis ball) being dropped, on the surface of the Earth, from a height of 1.22 meters and bouncing back upwards (assuming no air friction and no kinetic energy loss), seen from a distance of about 12.41 meters. The constant speed motion was simply the average instantaneous speed of the bouncing motion pattern and both patterns took one second to complete one cycle (in each trial, these cycles were repeated until a response was given). To prevent the emergence of synchronized global motions, on each trial each ball started its motion pattern at a randomly chosen point in its trajectory.

All stimuli were presented on a flat screen, with a resolution of 1920 × 1080 pixels (physical size of 52.7 × 29.6 cm). Participants sat in front of the monitor with their eyes fixed at a distance of 60 cm and their heads stabilized with a chin rest. The experimental tasks were programmed in Python using PsychoPy (Peirce, 2007, 2009). Participants' responses were registered by pressing one of two keys in a response box (Cedrus RB-540) to accurately measure response latency, and eye movements were recorded by GazePointGP3 at a sampling frequency of 150Hz.

Procedure and design

The task consisted of indicating, as fast but as accurately as possible, the presence or absence of the target in each block of trials, by pressing one of two coloured keys in a response pad: the green key indicating that the target was present and the red one that the target was absent. For half the participants the green key was positioned on the left side of the response pad and the red key on the right side; for the remaining participants this positioning was inverted (See Figure 1, panel A).

Figure 1. *A: Trial structure; B: Virtual grid depicting as white circles the possible locations onscreen for the balls; C: Spatial location as a function of time for the bouncing (continuous blue line) and constant speed (dashed orange line) motion patterns.*



Each participant performed four blocks of trials, with order counterbalanced with a Latin square design. In two of those four blocks, the target, which was present in the set of balls on half of the trials, was a bouncing ball with constant speed distractors; in the remaining two blocks, the target was a constant speed moving ball and the distractors were bouncing balls. Also, in two of those four blocks, the G-direction of whichever balls were moving with a bouncing pattern was inverted (downward or upward and leftward or rightward). The motion axes varied between participants, with 28 performing the tasks only with vertically and 27 with only horizontally moving stimuli.

Upon arrival at the laboratory, and after signing the informed consent, participants were briefed on the task. At the beginning of each block of trials, instructions were shown on screen accompanied by examples of the motion patterns for the target and distractors of that particular block. Once participants signalled that they understood the task, they performed 28 practice trials, randomly chosen from the experimental trials, where feedback regarding accuracy of the response (correct or incorrect) and response time was provided. After the practice trials but before the experimental trials, the eye tracker was calibrated with 9 reference points. Each trial started with an 81-pixel fixation cross (about 2.12º) on the centre of the screen which lasted for 800 ms, followed immediately by the stimuli which remained onscreen until a response was given. A blank screen was shown for 800 ms after each response and before the start of the next trial (see Figure 1, panel A).

The entire experiment thus conformed to a design given by 7 (set size: 2-8 balls) × 2 (target present or absent) × 2 (target motion pattern: bouncing or constant speed [across different blocks]) × 2 (G-direction: downward or upward and leftward or rightward [across different blocks]) × 10 (repetitions) with motion axes (vertical or horizontal) varied between participants, totalling 560 trials per participant (4 blocks of 140 trials each). The entire experimental session, including main blocks, practice trials, eye tracker calibration, resting periods in between blocks and debriefing took approximately 90 minutes to complete.

Results

Response times

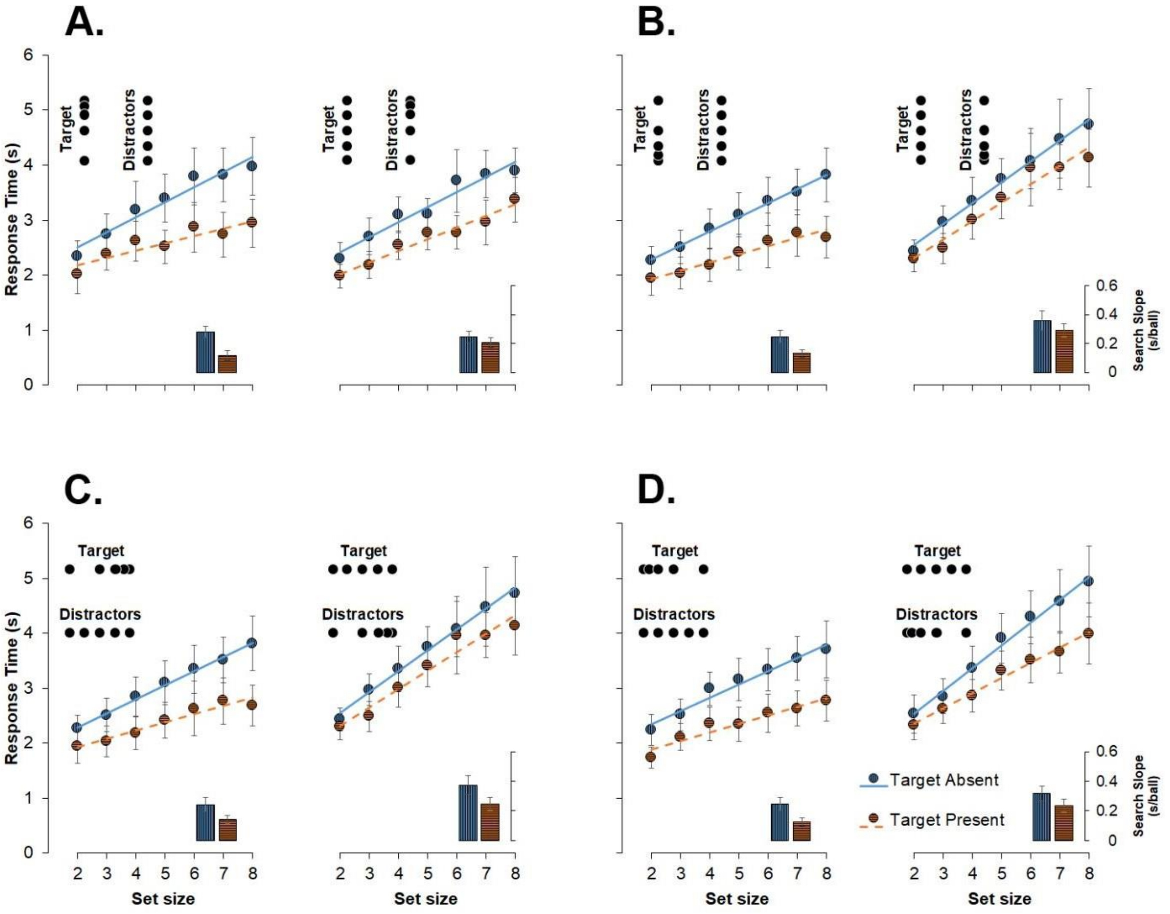
Figure 2 depicts the mean response times for correct responses as a function of the number of balls (abscissas) and presence/absence of the target (line parameter) for a bouncing target among constant speed distractors (left plot in each panel) and a constant speed target among bouncing distractors (right plot in each panel). The top panels refer to vertically moving balls, with panel A depicting results for a downward G-direction and panel B the results for an upward G-direction. Bottom panels depict results found for horizontally moving balls – Panel C for leftward G-direction and panel D for rightward G-direction (see inset pictograms). Overall, and as commonly found for visual search tasks, response times were found to increase linearly as set size increases, with higher slopes for trials where the target was absent. Importantly, the search slopes were found to be steeper for constant speed targets among bouncing distractors (right plots in each panel; see also inset bar plots), signalling less efficient visual searches under those conditions (that is, a visual search asymmetry), with a remarkable exception for the downward G-direction, where bouncing objects accelerated downward and decelerated upward, in conformity with Earth’s gravitational pull. For this latter condition, no visual search asymmetry is discernible and, if anything, slopes are shallower when searching for a constant speed target among bouncing distractors.

To statistically test the trends identified with visual inspection, response times were averaged across repetitions and subjected to a mixed ANOVA given by 2 (G-direction: downward/leftward or upward/rightward) × 2 (Target motion pattern: bouncing or constant speed) × 2 (Target present or absent) × 7 (set size: 2 to 8 balls), with motion axes (vertical or horizontal) as a between-subjects factor. In this and the remaining statistical analyses, whenever the sphericity assumption was not met, the Greenhouse-Geisser correction for the degrees of freedom was adopted.

Set size, $F(1.467, 77.751) = 79.524$, $p < 0.001$, *partial* $\eta^2 = 0.6$, and target's presence, $F(1, 53) = 50.692$, $p < 0.001$, *partial* $\eta^2 = 0.489$, significantly affected mean response times, which were found to increase both as the number of balls on screen increased and when target was absent. Furthermore, response times increased faster with set size when target was absent, as revealed with a statistical interaction, $F(4.177, 221.401) = 15.019$, $p < 0.001$, *partial* $\eta^2 = 0.221$. Target's motion pattern also led to a statistically significant effect, $F(1, 53) = 12.679$, $p < 0.001$, *partial* $\eta^2 = 0.193$, besides interacting with set size, $F(2.738, 145.12) = 9.219$, $p < 0.001$, *partial* $\eta^2 = 0.148$, and target's presence, $F(1, 53) = 6.153$, $p = 0.016$, *partial* $\eta^2 = 0.104$. In general, response times were found to be higher when searching for a constant speed target among bouncing distractors, in comparison with searching for a bouncing target among constant speed distractors. Furthermore, for the former condition, set size led to higher costs in response time with less difference between trials with or without the target. These trends reveal a search asymmetry, where a bouncing target is easier to find among constant speed distractors than a constant speed target among bouncing distractors.

Of particular relevance, though, G-direction was found to interact with target's motion pattern, $F(1, 53) = 13.54$, $p < 0.001$, *partial* $\eta^2 = 0.203$, with this interaction differing between horizontal and vertical motions, $F(1, 53) = 4.17$, $p = 0.046$, *partial* $\eta^2 = 0.073$. These outcomes reflect the fact that visual search asymmetry between searching for a bouncing or constant speed target was eliminated for vertically moving balls but only when bouncing balls (either target or distractors) conformed to gravitationally coherent motion (see Figure 2, and compare panel A with panels B, C and D). No other statistical effects were found.

Figure 2. *Mean response times as a function of set size (number of balls on screen; abscissas) and target's presence (line parameter) for bouncing targets among constant speed distractors (leftward plots in each panel) and constant speed targets among bouncing distractors (rightward plots in each panel). Inset bar plots depict the mean search slope of the linear relation between response times and set size.*



Note. All vertical bars depict the standard errors of the means.

Visual search slopes

To further explore the found outcomes, the slopes of the linear relations between response times and set size were calculated individually and for each combination of target's presence, target's motion pattern (bouncing or constant speed), G-direction (downward/leftward or upward/rightward) and motion axes (horizontal or vertical). These slopes were subjected to a mixed ANOVA with motion axes as a between-subjects factor.

Both target's motion pattern, $F(1, 53) = 16.578$, $p < 0.001$, *partial* $\eta^2 = 0.238$, and target's presence, $F(1, 53) = 45.174$, $p < 0.001$, *partial* $\eta^2 = 0.46$, modulated mean search slopes, which were bigger for trials with no target and overall higher for a constant speed target among bouncing distractors in comparison with bouncing targets among constant speed distractors. Again, the latter result reflects a visual search asymmetry in which targets subjected to acceleration/deceleration patterns are easier to find. G-direction did not result in a significant main effect, $F < 1$, but interacted with motion axes, $F(1, 53) = 5.482$, $p = 0.023$, *partial* $\eta^2 = 0.094$. Likewise, a three-way interaction between G-direction, target motion pattern and motion axes, $F(1, 53) = 4.342$, $p = 0.042$, *partial* $\eta^2 = 0.076$, was also found. Together, the latter results reflect a lack of visual search asymmetry specifically for those conditions where bouncing motions, either of the target or of the distractors, are coherent with gravitational motion (See Figure 2, panel A, inset vertical bars). Of relevance, an interaction between target's motion pattern and presence of target, $F(1, 53) = 5.546$, $p = 0.022$, *partial* $\eta^2 = 0.095$, was found to be statistically significant besides being changed depending on motion axes, $F(1, 53) = 4.25$, $p = 0.044$, *partial* $\eta^2 = 0.074$. These trends reflect the fact that the absence of visual search asymmetry for the conditions where bouncing patterns conform to Earth's gravity are mostly due to a higher efficiency in correctly detecting that a constant speed target was absent among bouncing distractions, rather than correctly detecting its presence. No other main effects or interaction were found to reach the statistical significance level.

Proportion of hits and false alarms, Sensitivity and response criteria

For those trials where the target was present, individual hit and false alarm rates were calculated for each combination of target's motion pattern (bouncing or constant speed), set size, G-direction (downward/leftward or upward/rightward) and motion axes (horizontal or vertical) and used to calculate sensitivity (d') and response criteria (c) measures (see Figure 3). The latter were both subjected to mixed ANOVAs, with motion axes as a between-subjects factor. As typically found in visual search experiments, d' was found to significantly decrease with increasing set sizes, $F(4.468, 236.798) = 52.645$, $p < 0.001$, *partial* $\eta^2 = 0.498$. Furthermore, d' was bigger for bouncing, as compared to constant speed, targets, $F(1, 53) = 34.669$, $p < 0.001$, *partial* $\eta^2 = 0.395$, besides decreasing less for the former with increases in set size, $F(6, 318) = 2.336$, $p = 0.032$, *partial* $\eta^2 = 0.042$.

The direction towards which the target or the distractors accelerated (G-direction) did not affect d', $F < 1$, but it did significantly interact with the axes of motion, $F(1, 53) = 4.658$, $p = 0.035$, *partial* $\eta^2 = 0.081$, such that mean d' was overall lower for a downward G-direction, in comparison with upward (with little differences between leftward and rightward). Importantly, G-direction also interacted with target motion pattern, $F(1, 53) = 20.398$, $p < 0.001$, *partial* $\eta^2 = 0.278$, and this latter interaction was significantly modulated by the axes of motion, $F(1, 53) = 8.365$, $p = 0.006$, *partial* $\eta^2 = 0.136$. Together, these effects reveal that while for the horizontal motion participants were more sensitive in finding bouncing targets, irrespective of the G-direction, for vertical motion that was the case solely for the upward G-direction. When either the target or the distractors accelerated downward and decelerated upward, in conformity with a gravitational pull, there were no differences in the sensitivity to detect constant speed or bouncing targets, respectively (see Figure 3, panel A). Finally, for that same condition (downward G-direction), increases in set size reduced mean d' equally for both bouncing and constant speed targets, as revealed with a significant interaction between G-direction, motion pattern, set size and axes, $F(6, 318) = 2.564$, $p = 0.019$, *partial* $\eta^2 = 0.046$. These outcomes were mostly due to the fact that for the downward G-direction, and in contrast with the remaining directions, the effect of set size on hit rate did not differ between bouncing and constant speed targets, while false alarms for constant speed targets increased slightly with set size (see Figure 3, panel insets).

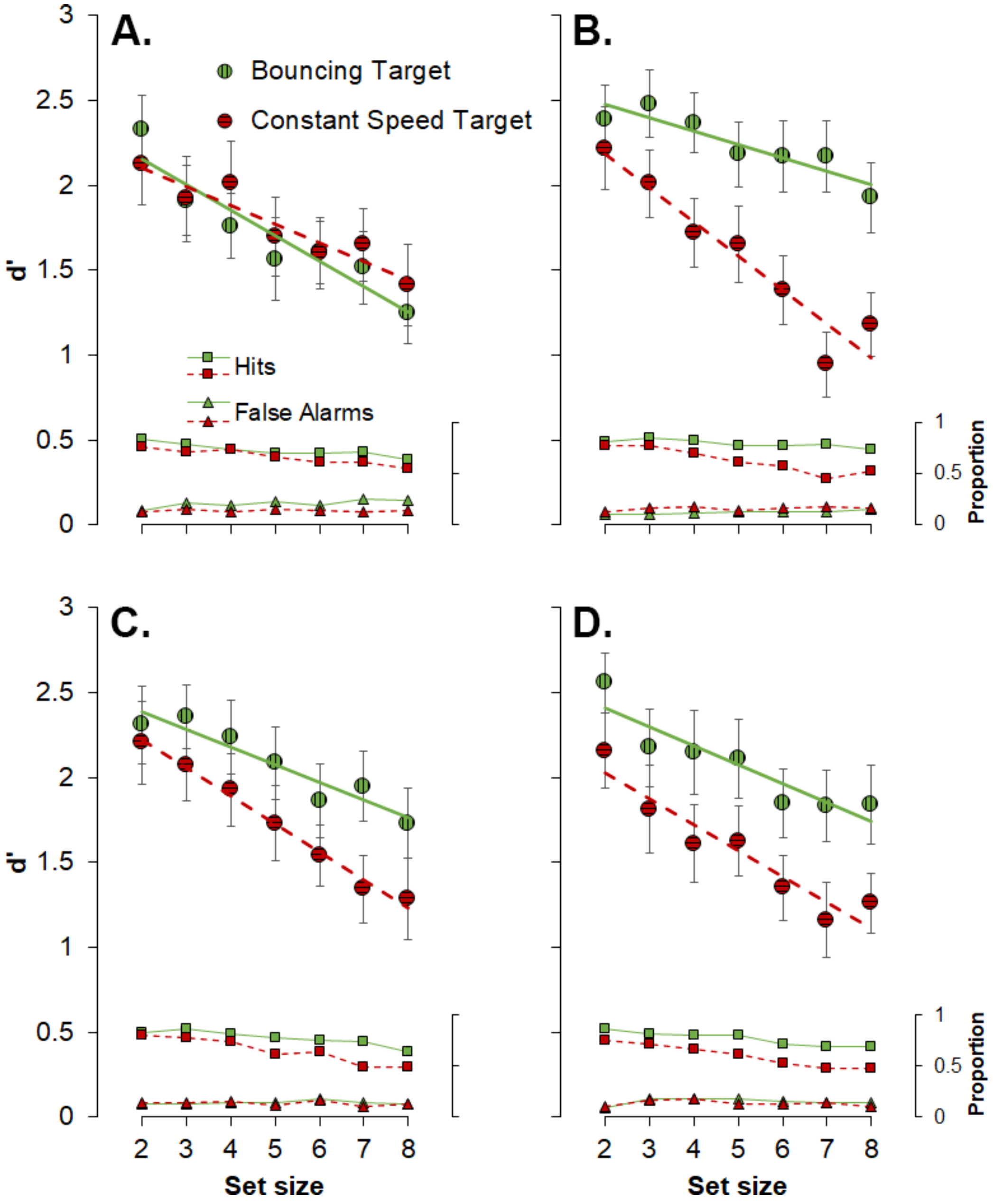
Eye movements

Due to technical problems (calibration failure and data loss due to lack of disk space), eye tracking data of six participants were lost. For the remaining 49 participants (25 in the vertical axes condition), number of total fixations per trial, mean fixation duration per trials and proportion of target fixations (for trials where the target was present) were calculated and subjected to a mixed ANOVAs with motion axes as a between subjects-variable and set size, target motion pattern, G-direction and target's presence (except for proportion of target fixations) as repeated-measures variables.

Expectedly, mean number of fixations increased as a function of set size, $F(1.1, 51.681) = 77.173$, $p < 0.001$, *partial* $\eta^2 = 0.621$, and were also higher for trials where the target was absent, $F(1, 47) = 22.863$, $p < 0.001$, *partial* $\eta^2 = 0.327$. The effect of set size and target's presence were also found to magnify each other, $F(3.268, 153.593) = 11.851$, $p < 0.001$, *partial* $\eta^2 = 0.201$. When participants were searching for constant speed targets among bouncing distractors they performed significantly more fixations, in comparison with when they were searching for bouncing targets among constant speed distractors, $F(1, 47) = 7.434$, $p = 0.009$, *partial* $\eta^2 = 0.137$, and more so as set size increased, $F(1.436, 67.485) = 9.504$, $p <$

0.001, *partial* $\eta^2 = 0.168$. These latter results corroborate behavioural data in that searching for a bouncing target was, overall, more efficient than searching for a constant speed target.

Figure 3. *Mean d' as a function of set size (abscissas) and target's motion pattern (line parameter) for downward (panel A), upward (panel B), leftward (panel C) and rightward (panel D) G-directions. Inset plots depict the corresponding proportion of hits (square marker) and false alarms (triangle marker).*



For seventeen participants, no fixations in the trials of at least one condition were recorded, mostly due to poor calibration and/or changes in the positioning of their heads. For the remaining 32 participants, overall mean fixation duration was found to slightly decrease with set size, $F(3.192, 95.764) = 2.852$, $p = 0.038$, *partial* $\eta^2 = 0.087$. Also, for those participants, the proportion of target fixations when it was present was found to decrease with set size (from about 56%, when only 2 balls were present, to 13%, when there were 8 balls onscreen), $F(4.079, 126.437) = 102.112$, $p < 0.001$, *partial* $\eta^2 = 0.767$. Finally, bouncing targets, when present, were more often fixated (29.3%) than were constant speed targets (27%), $F(1, 31) = 7.305$, $p = 0.011$, *partial* $\eta^2 = 0.191$, again in conformity with behavioural outcomes.

Discussion and Conclusion

The present study aimed to explore a possible manifestation of an internal model of gravity with a visual search task involving moving stimuli. Specifically, observers were required to indicate the presence/absence of a bouncing target among constant speed distractors or a constant speed target among bouncing distractors, with the bouncing direction (either of targets or distractors) being systematically varied. Overall, visual searches for bouncing targets among constant speed distractors were robustly more efficient than searches for constant speed targets among bouncing distractors – that is, a visual search asymmetry (Wolfe, 2001). Manifestly, this outcome reflects the fact that bouncing motions involve a pattern of accelerations/decelerations which renders it perceptively more salient than a constant speed motion pattern, particularly at the point in its trajectory where the target “bounces” and its instantaneous speed reaches a maximum (see Figure 1, panel C; cf. Nakayama and Motoyoshi, 2017).

Interestingly enough, visual search asymmetry vanished specifically for those conditions where the bouncing motion patterns (of the target or the distractors) conformed to the expected dynamics of Earth’s gravitational pull (accelerating downward and, after bouncing, decelerating upward). Arguably, this outcome reflects a familiarity effect, where a constant speed target is easier to find in a context of distractors moving in accordance with expected visual gravitational motion, rendering its motion unexpected and, hence, unfamiliar.

Thus, on the one hand, bouncing targets, likely due to low-level features of visual processing of accelerations (Nakayama & Motoyoshi, 2017) are easier to detect than constant speed targets; on the other hand, within a block where bouncing motions conform to the expected dynamics of gravitational acceleration, as putatively outputted by an Internal Model of Gravity, constant speed targets, due to their unexpected and unfamiliar motion pattern, are easier to detect (Flowers & Lohr, 1985; Frith, 1974; Lubow & Kaplan, 1997; Malinowski & Hübner, 2001; Richards & Reicher, 1978; Wang et al., 1994). Both factors act in opposing directions and, consequently, seem to cancel out in that condition where the latter is of relevance – when bouncing objects accelerate downward and decelerate upward –, accounting for the vanishing of the visual search asymmetry triggered by the former. In accordance with this explanation, for the downward G-direction condition, we also found evidence for a slightly increased efficiency in detecting the absence of a constant speed target among bouncing distractors. Stated differently, and to the degree that our account is the case, observers more promptly and efficiently rejected the presence of an object moving in a pattern distinct from the kinematics expected from an Internal Model of Gravity.

Measures of sensitivity (d') provided further evidence for the involvement of an Internal Model of Gravity. While sensitivity to detect targets decreased with increases in set size, as commonly found in visual search tasks (Palmer et al., 2011; Yang & Wolfe, 2020), important differences emerged between bouncing and constant speed targets. Overall, sensitivity for the detection of bouncing targets decreased less with set size than for the detection of constant speed targets – that is, across all instances of set size, the detection of bouncing targets was easier and more efficient. Furthermore, those sensitivity differences were mostly due to the fact that hit rate for constant speed targets decreased more with increases in set size. In contrast, however, when the patterns of accelerations/decelerations of the bouncing objects conformed to what would be expected due to Earth's gravitational pull, sensitivity to detect a bouncing target did not differ from the sensitivity to detect a constant speed target. To a great extent, this outcome has to do with the fact that, for this condition and with increases in set size, the decrease in the hit rate of constant speed targets was counterbalanced with a slight increase in the false alarm rate for bouncing targets. In other words, in the harder detection conditions (with more objects onscreen), observers were slightly more prone to wrongly indicate that a bouncing object was present (with all stimuli moving at a constant speed) while being slightly less prone to fail to detect a constant speed target actually present among bouncing distractors. The latter observation is of particular relevance, for it is neatly in accordance with the findings reported by McIntyre and colleagues (2001). In that study, astronauts were asked to catch balls launched from the wall of the Spacelab above their heads (thus perceived as a ceiling). Given the microgravity conditions, the balls actually moved at a constant speed – notwithstanding, and despite the fact that all astronauts could directly see the ball moving, anticipatory motor responses accorded with an expectation that the balls actually accelerated (as is the case on Earth). Likewise, in the present experiment, with all the objects moving with constant speeds, observers showed a tendency to erroneously report that a bouncing target was present, when searching for one moving in accordance with visual gravitational dynamics.

Finally, we also collected eye tracking measures. Among the several research lines which support that the human brain implements Internal Models of Gravity (Brouwer et al., 2006; Jörges & López-Moliner, 2017; Lacquaniti et al., 2013; McIntyre et al., 2001; Zago & Lacquaniti, 2005a, b; Zago et al., 2008, 2009) there is evidence that those also impact on patterns of eye movements (Delle Monache et al., 2015, 2019). As such, we did expect to find disparate patterns of gaze exploration between those conditions conforming or not to gravitational motion. Such was not the case albeit, to a great extent, due to technical issues (data loss and poor calibration for several participants). In any case, we uncovered some evidence that participants made fewer overall fixations, but those were more often directed to the target, when searching for bouncing targets among constant speed distractors. This result provides further support for our interpretation above that bouncing targets more efficiently captured attention, resulting in more efficient searches and detections. Notwithstanding, these outcomes did not appear to be changed when varying G-direction. On the one hand, and as stated above, our eye tracking data might not have been adequate to uncover existing trends. On the other hand, it might also be the case that in what refers to a visual search task, such as the one employed in the present study, the role of an Internal Model of Gravity either dispenses or does not affect patterns of overt ocular inspection. In previous research devoted to the modulation of eye movements by internal models of gravity, the focus has been on the behaviour when tracking one single object, conforming or not to gravitationally coherent dynamics (Barnett-Cowan & Harris, 2008; De Sá Teixeira & Hecht, 2014; Diaz et al., 2013; Huber & Krist, 2004; Pettorossi et al., 1998). In contrast, in the present study, our focus was on patterns of fixations on the overall locations of the stimuli, with not enough resolution to explore if and how participants tracked the objects throughout their trajectories. At this point, oculomotor behaviour and its possible links with the functioning of an internal model of gravity and visual search efficiency should be taken as a possible topic for future research.

As a concluding remark, the present work supplies evidence that an internal model of gravity modulates visual search efficiency, specifically for objects moving in conformity with the expected dynamics due to Earth’s gravity. Visual gravitational motion, rather than being a visual feature which aids its detection when present, seems to encompass expectations concerning motion dynamics enhancing the detection of violations to Earths’ gravitational pull.

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