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Research report

Mental imagery of gravitational motion

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ABSTRACT

There is considerable evidence that gravitational acceleration is taken into account in the interaction with falling targets through an internal model of Earth gravity. Here we asked whether this internal model is accessed also when target motion is imagined rather than real. In the main experiments, naïve participants grasped an imaginary ball, threw it against the ceiling, and caught it on rebound. In different blocks of trials, they had to imagine that the ball moved under terrestrial gravity (1g condition) or under microgravity (0g) as during a space flight. We measured the speed and timing of the throwing and catching actions, and plotted ball flight duration versus throwing speed. Best-fitting duration-speed curves estimate the laws of ball motion implicit in the participant's performance. Surprisingly, we found duration-speed curves compatible with 0g for both the imaginary 0g condition and the imaginary 1g condition, despite the familiarity with Earth gravity effects and the added realism of performing the throwing and catching actions. In a control experiment, naïve participants were asked to throw the imaginary ball vertically upwards at different heights, without hitting the ceiling, and to catch it on its way down. All participants overestimated ball flight durations relative to the durations predicted by the effects of Earth gravity. Overall, the results indicate that mental imagery of motion does not have access to the internal model of Earth gravity, but resorts to a simulation of visual motion. Because visual processing of accelerating/decelerating motion is poor, visual imagery of motion at constant speed or slowly varying speed appears to be the preferred mode to perform the tasks.

1. Introduction

Imagery is a mental experience of an object, scene, event or action that is not present to our senses. It has attracted considerable interest in view of its importance for thinking, memory, learning, motivation, sports training, and rehabilitation of disabled people (e.g., Kosslyn & Moulton, 2009; Ruffino, Papaxanthis, & Lebon, 2017; Schuster et al., 2011). Imagery bears some resemblance to sensory and motor experience, although the extent to which it shares representations and processes with normal perception and movement is debated (Grabherr & Mast, 2010; Kosslyn, 1994;

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Paivio, 1986; Pearson & Kosslyn, 2015; Pylyshyn, 2002; Thomas, 2016). Imagery often reflects ecological constraints, possibly guided by long-term memory of past experiences and internalization of the constraints (Grush, 2004; Ito, 2008; Jeannerod, 1994; Mast & Ellis, 2015; Moulton & Kosslyn, 2009; Shepard, 1984). For instance, chronometric studies showed that the time to inspect a mental image faithfully reflects the spatial metric properties of the real visual image (Kosslyn, Ball, & Reiser, 1978), as well as the temporal and kinematic characteristics of actual arm and body movements (Parsons, 1994), including Fitts's law (Decety & Jeannerod, 1996) and the 2/3 power law relating speed and curvature (Karklinsky & Flash, 2015; Papaxanthis, Paizis, White, Pozzo, & Stucchi, 2012).

On Earth, gravity is a ubiquitous constraint governing the motion of our body and external objects, and there is now ample evidence that gravity effects are taken into account by the brain in guiding motor responses (Angelaki, McHenry, Dickman, Newlands, & Hess, 1999; Ferri, Pauwels, Rizzolatti, & Orban, 2016; Gaveau, Berret, Angelaki, & Papaxanthis, 2016; Indovina et al., 2005, 2013; Jörges & López-Moliner, 2017; La Scaleia, Zago, & Lacquaniti, 2015; Lacquaniti, Carrozzo, & Borghese, 1993; Lacquaniti et al., 2015; Maffei et al., 2016, 2015; McIntyre, Zago, Berthoz, & Lacquaniti, 2001; Merfeld, Zupan, & Peterka, 1999; Miller et al., 2008; Papaxanthis, Pozzo, Popov, & Mcintyre, 1998; Tresilian, 1993; Zago et al., 2004). In particular, the limb motor activity involved in catching a falling ball or intercepting a target that is launched against a ceiling and falls back under gravity is accurately timed based on an implicit calculation of the gravity effects on the moving target (Indovina et al., 2005; Lacquaniti & Maioli, 1989b; Lacquaniti et al., 1993; Tresilian, 1993; Zago et al., 2004). Earth gravity is accurately taken into account during interception of falling objects even in the presence of partial visual information, as when the descent of the target is occluded over a substantial portion of the trajectory (Bosco, Delle Monache, & Lacquaniti, 2012; La Scaleia et al., 2015; Zago, Iosa, Maffei, & Lacquaniti, 2010). Earth gravity effects are still anticipated mistakenly in the interception of targets descending at constant speed, leading participants to move too early in real (McIntyre et al., 2001) or virtual microgravity (Zago et al., 2004). Overall, these observations are consistent with the idea that an internal model calculating the effects of Earth gravity (1g model) is stored in the brain, and is engaged by visual motion that is interpreted as affected by gravity (McIntyre et al., 2001; Zago & Lacquaniti, 2005b).

Here we tested whether the internal model of gravity is accessed when target motion is imagined rather than real. Specifically, in one series of experiments, we asked naïve participants to grasp an imaginary ball in the hand, to throw it against the ceiling, and to catch it on rebound. They had to vary the magnitude of the throwing force across trials and, in different blocks of trials, to imagine that the ball moved under Earth gravity (1g condition) or under microgravity (0g) as during a space flight. The presence of a ceiling was necessary to simulate the condition of 0g, because at 0g the ball would come back only after bouncing against a surface. In control experiments, we removed the constraint of hitting the ceiling and asked the participants to throw the imaginary ball vertically upwards at a given height and to catch it on its way down. By measuring the speed and timing of the throwing and catching actions, we were able to estimate the laws of ball motion implicit in the participant's performance, because 1g motions would correspond to a relationship between flight duration and throwing speed different from that corresponding to low gravity motions (see Section 2).

One might expect to find duration-speed values compatible with 1g but not with 0g, under the assumption that imagery of ball motion draws from stored memories of previously experienced similar motions and/or that imagery involves the same internal 1g model that is engaged by interactions with real targets. Instead, we found duration-speed values compatible with low gravity in both the main experiments with the ceiling and the control experiments without the ceiling. Preliminary results from this work have appeared in Gravano (2009).

2. Theoretical curves of ball flight duration versus throwing speed

Let us consider the motion of a ball thrown vertically upwards with initial speed V_T toward a ceiling placed at a distance K above the hand (main experiments). Under the influence of Earth gravity ($1g = 9.81$ m sec^{-2}), the ball returns in the hand after a time interval ΔT from launch time defined by Eq. 1:

$$\Delta T = \frac{2}{g}\left(V_T - \sqrt{V_T^2 - 2gK}\right) \tag{1}$$

For the sake of simplicity, here we assume zero air drag, elastic bounce on the ceiling, and the same distance K between hand and ceiling at throwing and catching time, but in a subsequent section we relax these constraints to test alternative solutions. If the ball is thrown repeatedly at different initial speeds, the resulting data points will be scattered along the red curves of the ΔT versus V_T graph of Fig. 1A. These duration-speed curves are non-monotonic because the ball reaches the ceiling only for $V_T \geq \sqrt{2gK}$, whereas it falls back without contacting the ceiling for $V_T < \sqrt{2gK}$. Three such curves are plotted in Fig. 1A, corresponding to $K = 1$, 2 or 4 m (close to the values of the present experiments); the higher the ceiling, the higher are the corresponding curves and the limiting value of V_T. As for the condition in which a ball is launched vertically upwards but falls back without contacting the ceiling (control experiments), all data points (ΔT, V_T) lie on the straight line through the origin with slope 2/g. Once more, the higher the launch, the greater are the ΔT, V_T values: $\Delta T = 2V_T/g$, $K = V_T^2/2g$.

The results would be very different in the absence of gravity effects (0g), as in a spacelab. First, the ball would come back only after hitting a surface, and in this case it would return in the hand after a ΔT interval given by Eq. 2:

$$\Delta T = \frac{2K}{V_T} \tag{2}$$

Moreover, in contrast with the 1g condition, at 0g any throwing speed V_T, however small, would propel the ball against the ceiling. The ΔT versus V_T curves predicted by 0g dynamics are monotonically decreasing, hyperbolic functions