**Provisional title:**

“Probing the role of the vestibular system in reward-based attention: a pre-registered report”

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**Provisional abstract**

Intrinsically rewarding stimuli favour attentional capture (AC) in humans. The physiology of this phenomenon is currently poorly understood, and various neural candidates might subserve the interplay between motivation and spatial attention. A method for interfering with this circuitry would provide more compelling evidence and be a major advance for the cognitive and clinical neuroscience of motivation.

Most brain stimulation techniques (i.e. TMS, tDCS) typically do not allow for stimulation of deep brain structures, their effect being limited to superficial areas. In contrast, Vestibular Stimulation (VS), via galvanic or thermal activation of the peripheral organs devoted to balance, have been consistently shown to produce reliable activation of deep structures involved in mood and affective processing. VS is routinely employed in medicine and physiology, but a deeper understanding of its cognitive effects is needed.

Here we propose having healthy participants perform a simple discrimination task assessing the interaction between attention and motivation, while receiving Galvanic Vestibular Stimulation (GVS). The main objective of our manipulation is to assess whether the modulation of brain activity via GVS may modulate the degree of AC, i.e. facilitate the orienting of attention towards rewarding stimuli. Such a project could not only greatly advance our knowledge on the neural circuitry underlying the interplay between reward processing and visuospatial attention but also provide novel clinical and therapeutic insights.

**1. Introduction**

Dr. Brown is attending a tedious talk, stuck in the centre of a crowded theatre. He has just arrived in town after a long and difficult journey that made him miss lunch. Now he’s so famished he could “eat an entire horse”. Meanwhile, people in charge of the catering are finally finishing preparing the generous buffet, and long tables full of delicacies are placed along the theatre’s sidewalls. In this scenario Dr. Brown has a very well-defined “priority map” (Serences, 2008), and while he is trying to be attentive to the speaker he also can’t help peeking at those tasty sandwiches. What happens in his brain while the food exerts such a magnetic attraction on him, grabbing his eyes? This is both an intriguing and fundamental question, if we consider that the extreme deviation from this widely spread behaviour – i.e. aberrant and excessive attraction for intrinsically rewarding distracters – seems to be a recurrent feature in a variety of addiction disorders (Field, Munafò, & Franken, 2009, for meta-analysis).

To understand the impact reward exerts on **Attentional Capture (AC)** in a laboratory setting, several studies have successfully focused on monetary reward (a secondary need) because it’s easier to manipulate parametrically and does not depend on transient states. Both immediate and long-term effects of monetary reward have been demonstrated in a variety of tasks (Anderson, Laurent, & Yantis, 2011; Anderson & Yantis, 2012; Camara, Manohar, & Husain, 2013; Chelazzi, Perlato, Santandrea, & Della Libera, 2013; Della Libera & Chelazzi, 2006; Engelmann & Pessoa, 2014; Hickey, Chelazzi, & Theeuwes, 2010; Munneke, Hoppenbrouwers, & Theeuwes, 2015; Theeuwes & Belopolsky, 2012). For instance, in visual search tasks, general performance (Anderson et al., 2011; Chelazzi et al., 2014) and oculomotor behaviour (Bucker, Belopolsky, & Theeuwes, 2015; Camara et al., 2013; Theeuwes & Belopolsky, 2012) can be biased by task-irrelevant distracters that were previously rewarded.

A wide network of interacting regions and chemicals (Grabenhorst & Rolls, 2011), every node being in charge of different cognitive operations, has been ascribed to the reward processing circuit in the brain. This network includes, among others, the **Anterior Cingulate Cortex (aCC)** (Silvetti, Alexander, Verguts, & Brown, 2014). From an anatomical point of view, the aCC is an important hub linking areas in charge of evaluating reward desirability (e.g. orbitofrontal cortex, amygdala) and areas devoted to attentional selection and motor responses (e.g. parietal areas) (Amiez, Joseph, & Procyk, 2006; Heuvel & Sporns, 2013; Lavin et al., 2013; Morecraft et al., 2012). It has a well-established role in monitoring outcomes and selecting the most appropriate and rewarding choice for future events (Amiez et al., 2006; Botvinick, Cohen, & Carter, 2004; Bush et al., 2002; Hadland, Rushworth, Gaffan, & Passingham, 2003; Rushworth, Walton, Kennerley, & Bannerman, 2004) and reward-based learning (Kennerley, Walton, Behrens, Buckley, & Rushworth, 2006; Lecce et al., 2015). Importantly, it also appears involved in the allocation of attentional resources towards rewarding stimuli in space (Hickey et al., 2010; Lecce et al., 2015; Mesulam, 1999). However, the aCC is unlikely to be the sole substrate of the interplay between motivation and attention, and some of the aforementioned features are also shared by other key areas (Engelmann et al., 2009) such as the Temporo-Parietal Junction (TPJ) (Bisley & Goldberg, 2010; Mohanty, Gitelman, Small, & Mesulam, 2008), and the basal ganglia (Anderson, Laurent, & Yantis, 2014).

Interestingly, activation of all these structures has often been reported following non-invasive brain stimulation techniques such as caloric vestibular stimulation in PET (Bottini et al., 1994, 2001) and fMRI studies (Fasold et al., 2002; Suzuki et al., 2001), as well as following **Galvanic Vestibular Stimulation (GVS)** (Bense, Stephan, Yousry, Brandt, & Dieterich, 2001; Cyran, Boegle, Stephan, Dieterich, & Glasauer, 2015; Lobel, Kleine, Bihan, Leroy-Willig, & Berthoz, 1998; Stephan et al., 2005). The latter technique consists of peripheral stimulation of the vestibular nerve (see Curthoys & MacDougall, 2012, for debate) through the application of small intensity currents over the mastoid bones (Fitzpatrick & Day, 2004; Utz, Dimova, Oppenländer, & Kerkhoff, 2010). It has risen in popularity in recent years and proved to be safe and promising tool for providing causal links between brain areas and behavioural performance (Been, Ngo, Miller, & Fitzgerald, 2007), with interesting applications for clinical cases. It also offers a unique way to modulate the activity of deep brain structures. Indeed, vestibular input is centrally represented in an extended network of multisensory areas (Guldin & Grüsser, 1998), including areas nearby TPJ, the operculo-insular/retroinsular cortex (Dieterich & Brandt, 2008, for a review; Lopez, Blanke, & Mast, 2012, and zu Eulenburg, Caspers, Roski, & Eickhoff, 2012, for meta-analyses), and deep and limbic cortices, including cingulate areas (Guldin, Akbarian, & Grüsser, 1992; Guldin & Grüsser, 1998). Patients with vestibular neuritis exhibit an altered pattern of brain activations and deactivations similar to that observed following GVS (Alessandrini et al., 2013; Becker-Bense et al., 2013; Bense et al., 2004; Dieterich & Brandt, 2008). In such clinical populations, aCC is part of a large network whose activity is altered with respect to healthy participants (Helmchen, Ye, Sprenger, & Münte, 2013), perhaps with some role in explaining the high comorbidity with psychiatric symptoms of anxiety and depression (Gurvich, Maller, Lithgow, Haghgooie, & Kulkarni, 2013; Smith & Zheng, 2013).

Much of the interest around vestibular stimulation techniques arises from their known effectiveness in modulating spatial biases. For instance, they affect the setting of basic spatial coordinates, e.g. the subjective perception of “straight ahead” (Karnath, Sievering, & Fetter, 1994), of verticality (Mars, Popov, & Vercher, 2001), or the midpoint of a visual line (Ferrè, Longo, Fiori, & Haggard, 2013). While they do not seem to affect covert spatial attention (Rorden, Karnath, & Driver, 2001), vestibular stimulation nevertheless ameliorates the clinical manifestations of spatial neglect (Cappa, Sterzi, Vallar, & Bisiach, 1987; Rubens, 1985), possibly following parietal activations. By contrast, few studies have suggested that vestibular stimulation has the potential to also reach areas implicated in mood, affective processing, and motivation (Carmona, Holland, & Harrison, 2009; Mast, Preuss, Hartmann, & Grabherr, 2014; Preuss, Hasler, & Mast, 2014; Preuss, Mast, & Hasler, 2014), and a few case reports testify their effectiveness on psychiatric disorders such as mania (Dodson, 2004; Levine et al., 2012, for a review see also Lopez, 2016). Experimental evidence is still scarce, though. In one notable exception, Preuss, Hasler, et al. (2014) reported that CVS can modulate affective control in a Go/No-go task that exploited emotional images as visual stimuli. In their study, left-cold CVS concurrently decreased affective control (as assessed by means of the *d’* sensitivity index) for positive images and self-reported positive mood ratings. Brain activations following vestibular stimulations, thus, extend to several of the deep areas involved in the processing of rewards. Nausea itself, such that originating from visual-vestibular mismatches, has been interpreted in light of evolutionary theories, underlining its role in preventing the search for and exploitation of goods that previously resulted in aversive reactions (Treisman, 1977). Under this view, nausea has been proposed to participate in the process of aversive conditioning, causing sensitization to repulsive stimuli that induce such unpleasant interoceptive sensations (Treisman, 1977). Based on this converging evidence, the aim of this study is therefore to take advantage of GVS to test the hypothesis that the vestibular system is involved in the processing of motivational stimuli. Our first question is whether perturbing the vestibular system results in altered sensitivity to rewards. Our second question is then whether attentional capture is further modulated by GVS.

We will administer to healthy subjects GVS and a task assessing the interplay between attentional and motivational cues (Bucker & Theeuwes, 2014). AC has been described in a number of different paradigms. For the sake of this study, we will exploit a well-established discrimination task with lateralized exogenous cueing (Posner, Snyder, & Davidson, 1980). When cues appear on the same spatial position of the target to be discriminated (i.e. valid trial), a behavioural advantage (i.e. validity gain) is commonly observed (Posner et al., 1980). In a few circumstances (e.g., non-predictive exogenous cues, long time intervals between cue and target) validity gain turns into **Inhibition Of Return (IOR)**: performance is impaired for cued locations, possibly foreshadowing a mechanism to optimally explore the visual environment by avoiding previously attended locations (Chica, Martín-Arévalo, Botta, & Lupiáñez, 2014). The main advantage of these indices is their ability to assess purely attentional processes, setting apart other motor and perceptual factors (Posner et al., 1980). Besides spatial information, cues will provide participants with motivationally-relevant information (i.e. the colour of the cue will predict the monetary gain for that trial). Any modulation of the validity effect as a function of the allotted reward, thus, informs about the interaction between attentional and motivational processes.

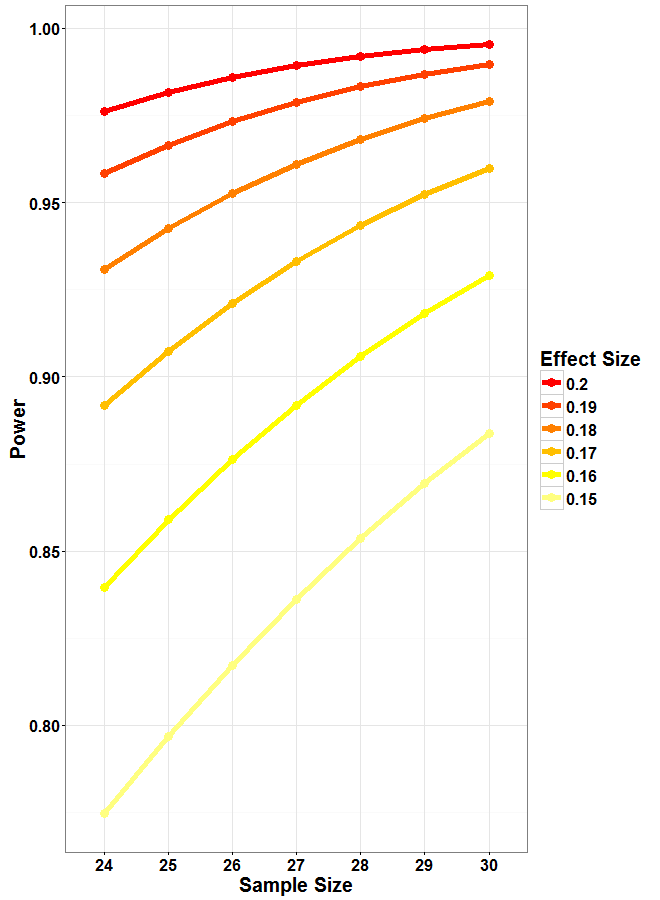
A few studies previously assessed the validity of such paradigm. For example, Munneke et al. (2015) found that validity gain is enhanced when cues predict large, as compared to smaller rewards, suggesting attentional capture. In their discrimination task, Munneke et al. (2015) attached reward information on exogenous, peripheral cues on a trial by trial basis. Other settings yielded partially inconsistent results (Baines, Ruz, Rao, Denison, & Nobre, 2011; Bucker & Theeuwes, 2014; Engelmann & Pessoa, 2014; Small et al., 2005). The inconsistency might reflect the sensitivity of such attentional paradigm to even small differences in the experimental setting (Chica et al., 2014). Yet, this task appears to be an appropriate choice for at least two reasons: 1) it highlights the overall beneficial effect of reward on performance (i.e., not in interaction with spatial attention); 2) neuroimaging studies have found that activity in brain regions coding for spatial expectancy is modulated as a function of reward (Baines, Ruz, Rao, Denison, & Nobre, 2011; Engelmann et al., 2009; Small et al., 2005).

With this study, we thus aim to assess the behavioural effects of rewards over spatial attention, with particular reference to the validity effect, and then test the concurrent impact of a vestibular stimulation. We will thus assess any modulation of the validity effect following rewarding cues and during GVS, i.e. the three-way GVS by Reward by Validity interaction, seeking for a signature of the role of the vestibular system. Although the observed brain activations following GVS might possibly suggest a boost of attentional capture phenomena during its administration, it’s unclear that such brain activation invariantly leads to the enhancement of a behavioural effect (i.e., inhibitions might be expected as well). To the best of our knowledge, to date there exists no evidence on the effect of GVS on reward processes. Thus, no directional starting hypothesis is posed on the two-way (GVS by Reward) and three-way (GVS by Reward by Validity) interactions. The scope of our study is to test whether the vestibular system is implicated in the processing of reward. By attempting to answer the question “whether” instead of “how”, we engage ourselves in making cautious post-hoc claims, should this modulation actually exist. This study would provide a first proof of principle on the role of the VS in the interplay between reward and attention that could pave the way to future clinical and neuroimaging studies.

**2. Material and methods**

**2.1 Participants**

A tentative power analysis was performed through the G\*Power software (Faul, Erdfelder, Lang, & Buchner, 2007). We computed a priori power for ANOVA design (F tests family, repeated measures - within factors). We used, as input parameters, an effect size f = 0.17, alpha level = 0.05, correlation among repeated measures = 0.5, and assumed no non-sphericity correction (1). Our design only considers 1 group of subjects with 18 repeated measures (GVS by Reward by Validity, 3x3x2). A power of 90% is achieved at N = 25. To properly counterbalance all conditions in our design (see below in the methods) we need a sample size with a multiple of 6 subjects (3 levels of GVS x 2), thus we back-computed achieved power for N = 24 (89.1% power) and N = 30 (95.9% power). **Fig. 1** depicts the nominal power for a range of f values and different sample sizes (information provided in the supplementary materials).



**Fig. 1:** Nominal power is depicted as a function of arbitrary ranges of sample and effect sizes.

A maximum of 30 participants will thus be enrolled, but a first interim analysis is planned at N = 24. Type 1 error correction for optional stopping will be adopted (Lakens, 2014) in order to control for the cumulative Type 1 error rate (set to 0.05). Applying Pocock (1977) continuous boundaries for two sequential analyses not equally spaced is equal to adjust the alpha level to 0.043. Note that this new alpha threshold does not substantially impact the outcome of power analysis (a power of 90% is now reached at N = 26). Observed power will be computed and reported after data collection. A Bayesian secondary analysis through Bayes Factors (BF) will help in clarifying the extent to which the collected data will be conclusive (i.e., 0.33<BF10<3) (Schönbrodt & Wagenmakers, 2017).

Healthy young (18-38 years) volunteers, males and females, right-handed only, with normal or corrected-to-normal vision will be recruited. Recruitment will occur through advertising within the University of Lyon. Prior to the experiment, participants will complete a standard safety questionnaire in order to minimize the occurrence of side effects and check for exclusion criteria. Exclusion criteria are the following:

* Left handedness;
* Colour blindness (due to the fact that reward information will be conveyed via colours);
* History of epileptic seizures or close (first degree) familiarity with epilepsy;
* History of neurologic or psychiatric disorders (including recurrent migraine or headaches);
* History/presence of heart diseases;
* History of recurrent otitis media, vestibular disorders, or perforation of the tympanic membrane;
* Presence of metallic implants or metallic splinters in the body;
* Severe sleep deprivation during the last 24 hours;
* Consumption of psychotropic drugs, substances, or alcohol during the last 24 hours;
* Participation in other experiments involving stimulation techniques during the last week.

Only participants fulfilling the above criteria will be officially recruited for this study. Written informed consent will be obtained. This project has already received ethics approval from the relevant French Institutions under reference 2015-A00623-46 (FEEDBACK protocol). Demographic information about participants will be provided upon data collection.

**2.2 Behavioural tasks**

Participants will sit in a dimly lit, quiet room, their head restrained by a chinrest, facing a 15 inches large screen at a distance of approximately 57 cm. The open-source software OpenSesame (Mathôt, Schreij, & Theeuwes, 2011, http://osdoc.cogsci.nl/) will be used to display experimental stimuli on the screen and record the subjects response. Participants will provide responses by means of keyboard presses (on a standard QWERTY keyboard) using the index and middle fingers of their dominant hand.

Two tasks will be administered during GVS. The main task evaluates attentional assets and their modulation according to the rewards at stake **(Attention and Reward Task, ART)**. This part has been designed to last a maximum of 25 minutes. A control task **(Subjective Visual Vertical, SVV)** will be administered before the main task. SVV requires rotating visual segments until they appear to be in a vertical position. It is meant to provide independent evidence of GVS effectiveness, given that displacements occur towards the site of labyrinthine dysfunction (Böhmer & Rickenmann, 1995; Vibert, Häusler, & Safran, 1999) or anodal GVS stimulation (Mars et al., 2001; Saj, Honoré, & Rousseaux, 2006). Administering this task will thus provide evidence of a successful stimulation and a means to correlate the perceptual effects of GVS (effectiveness of the stimulation) with results obtained from the ART task. The scripts to run these tasks can be found in the supplementary materials.

Finally, a brief evaluation of subjective feelings and sensations experienced during each session will be administered. It will be useful to monitor participants’ distress and task compliance across the different days of the experiment and GVS protocols.

**2.2.1 Attention and Reward Task (ART)**

A schematic depiction of the sequence of the task is illustrated in **Fig. 2**. Experimental stimuli will be white coloured and presented on a black background. Each trial will start with a fixation cross (1.8 x 1.8 cm) appearing at the centre of the screen. Participants will be instructed to maintain fixation and avoid eye movements throughout the session. Placeholders (3.5 x 3.5 cm) will be also presented at both sides of the screen, at a distance of 8 cm from the centre (8° of visual angle). The fixation phase will last 750 ms (with a 150 ms uniform jitter). Then, one of the two boxes (the left and right with a probability of 50% each) will change colour (100 ms). Different colours, red, green or blue will inform the subject about the possibility to receive a **Reward** of 0, 2, or 10 points in case of a correct response in the following phase. Colour-reward associations will change randomly for each participant. Then, placeholders are returned to their default colour and presented on screen for 600 ms (jitter: 135 ms; total Stimulus Onset Asynchrony, SOA: 700 ms). After this SOA elapsed, either a square or a circle (1.5 x 1.5 cm, filled-white) is randomly presented within one of the two placeholders. Target **Side** (left, right) will be the same (valid) or different (invalid) to that of the cue in half of the trials, thus the peripheral exogenous cue is non-predictive (**Validity** 50%). Participants will be informed that these contingencies are equiprobable. Such a procedure (e.g. a relatively long SOA, exogenous non-predictive cueing) is most commonly linked to **Inhibition Of Return (IOR)** (Chica et al., 2014; Klein, 2000), which consists of an impaired performance for previously cued locations. IOR is thought to reflect a phenomenon that is complementary (yet distinct) to the classic validity gain occurring at short SOAs (Klein, 2000). Being defined in terms of validity costs, it still indexes the allocation of attention in space and will thus be appropriate to respond our experimental questions (also see Bucker & Theeuwes, 2014).

The target will remain on screen for a maximum of 750 ms or until a response is provided. Participants will be required to press the button corresponding to the previously presented geometric shape (contingencies counterbalanced across participants). To ensure that discrimination is unconfounded by any response bias/motor preparation, the response dimension will be orthogonal to stimuli lateralization (that is, the DOWN and UP arrows opposed to left/right stimuli presentation will be used, see Spence & Driver, 1994). Reward is provided only in case of a response that is both accurate and given within a 100-500 ms time window, with the purpose of: i) discouraging anticipations, and ii) providing a challenging upper limit, hence promoting active efforts to achieve rewards (expected success rate: 85-90%). A feedback will be eventually presented for 1000 ms. The feedback reports the outcome of the trial (correct, incorrect, slow, or fast response). Following each correct response, the amount of points earned is reported, together with the overall amount of euros gained so far.



**Fig. 2:** Graphical representation and time-course of a typical trial of the ART.

The experiment will consist of 432 trials (Shape, Side, Validity, Reward = 2x2x2x3, 18 trials per cell). It will start with a brief practice block composed of 18 randomly selected trials. Then, three blocks of 144 trials each will be administered, with breaks in between that summarise participants’ performance. Each of the four experimental variables is equi-represented within each block and randomly selected. The whole experiment has been designed to last about 25 minutes, to accommodate the maximum time limit for GVS administration (see below).

**2.2.2 Subjective Visual Vertical (SVV)**

One segment (17 cm, 2 mm wide; white-coloured, over a black background) will be presented at the centre of the screen. Its starting orientation will vary randomly between 1 and 20 degrees from the geometric (objective) vertical, in both clockwise and counter-clockwise directions (counterbalanced). Participants are asked to align the segment along the vertical plane by manually rotating it clockwise or counter clockwise using the keyboard. Segments’ orientation changes with steps of 0.1° (between -1.6 and 1.6 degrees from the vertical) up to steps of 0.7° for more extreme responses (>19°). Participants will thus be informed that a counting strategy will be counter-productive, and asked to stress accuracy over speed.

A circular black panel will cover the borders of the screen, to minimize the use of external anchoring points to perform the task. For the same reason, the experiment will be performed in darkness. A total of 24 trials will be given.

As dependent variable, the orientation of the SVV (in degrees) will be stored. Positive values will reflect a shift occurring clockwise (i.e. towards the right ear), while negative values will reflect a counter-clockwise bias.

**2.2.3 Subjective experienced sensations**

After each session, we will ask participants questions exploring their subjective experience with the stimulation they received. We will ask them to grade their illusion of body movement (left-right, up-down, forward-backward), of head tilting, and of the visual scene moving; their degree of nausea and vertigo; the feeling of some part of their body changing size; the amount of itching, burning, and overall distress due to the electrodes. Furthermore, three questions will specifically concern their feelings about the ART task: the amount of concentration devoted to the task, the amount of motivation to perform well, and the specific motivation prompted by the rewards at stake.

Each question will be presented on a computer screen, on top of a horizontal visual line representing a scale continuum. Subjects will grade their experience by means of mouse-clicks on the line. The standardized displacement from the objective centre of the segment (i.e., -100% for the leftmost end, 0% for the exact centre, +100% for the rightmost end) will be stored as the dependent variable for each question.

**2.3 Galvanic Vestibular Stimulation (GVS)**

GVS will be delivered *via* a commercial, CE approved, stimulator (BrainStim, EMS, Bologna). The application of small current intensities over the mastoid bones is associated to illusion of head and body movements towards the side of anodal stimulation, but induces very few adverse effects with stimulation up to 1.5 mA in both healthy and brain-damaged patients (Utz, Korluss, et al., 2011). A large study (N=255) found that about 10% of subjects felt slight itching and/or tingling sensations below the electrodes, but no occurrence of seizures, vertigo or nausea was reported (Utz, Korluss, et al., 2011).

Electric current of 1 mA will be administered continuously during each GVS session. A constant stimulation has been especially employed for rehabilitation purposes (Kerkhoff et al., 2011; Rorsman, Magnusson, & Johansson, 1999; Utz, Keller, Kardinal, & Kerkhoff, 2011). We will use spongy electrodes (14 cm^2 area) soaked with saline water and fixed in place with adhesive tape and a rubber band. Stimulation will be delivered only after an initial impedance check, to minimize potentially painful sensations. Three configurations will be adopted: Left- and Right- Anodal are considered active GVS conditions, inducing different (polarity dependent) effects. Electrodes are placed on mastoid processes symmetrically (that is, in the Left-Anodal montage the cathode is placed over the right mastoid bone, and *vice versa* for the Right-Anodal one). Left-Anodal stimulation activates mainly right hemisphere structures, whereas Right-Anodal activates comparatively more left hemisphere structures. A SHAM condition is also included, with electrodes placed symmetrically about 5 cm below the mastoids, above the neck, and distant from the trapezoidal muscles yielding proprioceptive signals (Lenggenhager, Lopez, & Blanke, 2007). The SHAM condition is included to control for unspecific factors of electrical stimulation (e.g., arousal, discomfort) that are known to have an important role in modulating performance in spatial tasks. The anode will be placed in this case on the left trapezoidal muscle (Ferrè et al., 2013). Participants will perform the behavioural tasks three times, in three different days, under each GVS condition (Left-Anodal, Right-Anodal and SHAM). The order of GVS type administration will be counterbalanced across subjects. Within each session, active stimulation will be delivered for a maximum of 30 minutes for safety reasons (Rossi, Hallett, Rossini, & Pascual-Leone, 2009).

Participants will receive a monetary contribution of 75 euros for their participation in the three sessions. They could receive an additional amount up to 25 euro/session according to their performance in the ART task, proportionally to the amount of points gained (over 1728 available points, hence ~ 0.015 euro per point).

**2.4 Analyses**

**2.4.1 Data pre-processing**

Data, excluding practice trials, will be analyzed with the open-source software R (The R Core Team, 2013).

The following reasons will lead to subjects’ replacement:

* Lack of participation in at least one of the three planned sessions. Participants might not attend all the planned sessions, for reasons that might or might not depend on the experimental setting itself (e.g., participants who experience particularly distressing sensations following one GVS session). Technical issues might arise in case of very high impedance on participants’ skins, and prevent GVS administration. Drop-out rate will be monitored continuously.
* Low performance (ART task). If the overall proportion of responses that is both correct and provided within 500 ms is below 0.6, a subject will be replaced. The threshold is set to 0.3 per cell when assessing performance in each Validity by Reward by GVS occurrence.
* Outlier classification (ART task). One of the cell means within the GVS by Reward by Validity interaction exceeds ±3 standard deviations from the subject’s mean.

Accuracy will be further analyzed only if the group mean is less than 95%, and if less than half of the subjects present more than 95% success rate (to avoid ceiling effects).

RTs will be only considered for responses that will be both accurate and given within the 100-500 ms time window.

**2.4.2 Statistical analyses**

**2.4.2.1 Attention and Reward Task (ART)**

Results will be analyzed through *mixed-effects multiple regression models* (Baayen, Davidson, & Bates, 2008) using the lme4 package for R (Bates, Maechler, Bolker, & Walker, 2014). Models will have a logistic link-function, appropriate for binary variables, when assessing accuracy. As a first step, we will define a model containing the most appropriate random effects. Theoretically, models including all the possible random effects (justified by experimental design) would lead to the most informative solution. However, complicated matrices often result in convergence problems in the face of a negligible increase in the amount of information provided or even overfitting (Bates, Kliegl, Vasishth, & Baayen, 2015). Random effects will thus be introduced sequentially, their effect on model fit assessed through **Likelihood Ratio Tests (LRT)**: residuals of each model will be compared, and the one with significantly lower deviance as assessed by a chi-squared test will be chosen.

*Random effects selection.* Restricted maximum likelihood will be used to test random effects. We will start with a random intercept for Subject only. Then, we will test random slopes, in the following order:

* GVS (3 levels: SHAM, Left-Anodal, Right-Anodal);
* Reward (3 levels: no reward, mid reward, high reward);
* Validity (2 levels: valid, invalid);
* Target Side (2 levels: left, right);
* Block (3 levels: block 1, 2, or 3);

Additionally, random slopes for Shape will be evaluated (but not the fixed effect). Note that Shape is confounded with response effector (e.g. square-index vs circle-middle finger), although the contingency is counterbalanced across subjects. The Block factor will be introduced to assess any modulation of rewards effectiveness over time (e.g. at the beginning or at the end of the stimulation).

Random slopes will be tested sequentially, meaning that each will be retained in the reference model as soon as a LRT supports its role. For example, in case of a significant increased fitting for the random slope of GVS, the random slope of Reward will be evaluated against a model including it. Once all six random slopes are evaluated, we will test random slopes for interactions. Only interactions of factors that were selected at the previous step will be tested. For example, if both (and only) the random slopes for GVS and Reward are found to be significant, only the two-way GVS by Reward will be further tested through LRT. The reason for this restriction is to have models fulfilling the marginality principle (each higher order term included only in presence of its lower level terms) and limit problems in model convergence.

*Fixed effect testing.* Maximum likelihood will be used to test fixed effects, using models with the final random effects structure. We will adopt type 2 sequential tests for the factors listed in the previous paragraph. In this approach, each effect or interaction is compared, through LRT, to a restricted model that excludes the effect itself. For example, a two-way interaction will be assessed by comparing the model including the interaction (and relative main effects, to fulfill the marginality principle) against a model that only includes the two main effects themselves. Differently from type 3 tests, type 2 tests are not conditional to other covariates being included in the model (thus, results do not depend on the presence/absence of “moderating” factors). The LRT outcome will then be the main inferential criterion, using p-values adjustments for multiple testing (see below) and an alpha level of 0.043 (see ¶ 2.1). Confidence intervals for the coefficients in case of informative models will be preferred over p-values.

For a Bayesian counterpart, **Bayes Factors (BF)** will be obtained through objective Cauchy-distributed priors (i.e., assuming that 50% of observed normalized effect sizes might fall in the -0.7 – +0.7 interval; Rouder, Morey, Speckman, & Province, 2012) using the BayesFactor package for R (Morey, Rouder, & Jamil, 2014), in the context of an ANOVA design. A Bayes Factor larger than 1 supports the alternative hypothesis, while a BF smaller than 1 supports H0; it is best used to grade the strength of evidence for one model over another.

*Procedure for dealing with non-convergence.* Despite the selection procedure mentioned above, convergence problems might still arise during the testing of both random and fixed effects. In order to minimize this problem, we will exploit the BOBYQA algorithm (Powell, 2009) and increase the maximum number of iterations up to 1020. Should this be insufficient, we will further simplify the matrix of random effects. We will start by dropping the correlation term between random slopes and intercept. Should this be insufficient, we will proceed in dropping one by one higher-order random slopes and all other terms, following the reverse order with respect to the one adopted in the selection phase.

*Corrections for multiple testing.* Four tests are the main focus of our proposal:

* The main effect of Reward;
* The Reward by Validity interaction;
* The GVS by Reward interaction;
* The three-way interaction: GVS by Reward by Validity.

Thus, these four tests represent our family of tests of interest. All other factors and interactions might cast interesting observations, but are not the focus of this work and thus represent a separate family of tests. For both families independently, we will apply p-value adjustments for false discovery rate (Benjamini & Hochberg, 1995).

**2.4.2.2 Subjective Visual Vertical (SVV)**

Procedures will be the same as above, but data will be trimmed, for each subject, at ± 2.5 standard deviations from the subject-specific mean.

The fixed (and random) factors that will be introduced and tested are:

* GVS (3 levels: SHAM, Left-Anodal, Right-Anodal);
* Starting Side (2 levels: clockwise, counter clockwise).

We expect a large, yet not of interest, effect for Starting Side – lines originally displayed as tilted clockwise associated with a clockwise response bias (similarly to what is typically found for line bisection tasks, Jewell & McCourt, 2000). P-values for GVS and the two-way GVS by Starting Side will be adjusted for false discovery rate and evaluated against an alpha level of 0.043.

**2.4.2.3 Subjective experienced sensations**

The SVV task represents the elective control for the effectiveness of GVS. In addition, we will evaluate subjective experience following GVS (e.g., probing subjective feeling of distress or motivation). We do not pre-register any specific analysis for these evaluations. This part will be exploratory with visually- and data-driven procedures. Should any inferential technique be deemed relevant for the scope of this study, it will exploit Bayes Factors with objective Cauchy-distributed priors. Given the explorative aspect of this evaluation, we set a more conservative threshold (BF10≥10), with respect to the previous two tasks.

**2.4.3 Outcome quality controls**

**2.4.3.1 Effect of Rewards**

We assumed that points, because they are converted into monetary rewards at the end of the experiment, will provide participants enhanced motivation to produce a valid response. This will be assessed through the main effect of Reward in the ART task (a significant LRT). As a second point, at least one coefficient in the model must indicate that performance improves for the maximum reward with respect to the null reward. Particular expectations are posed on reaction times, which are expected to be faster with high rewards and possibly with higher accuracy for high rewards. Should speed-accuracy trade-offs occur, we will deem this criterion as fulfilled if the proportion of valid trials (that is, both correct and timely) is higher for the maximum reward.

The aim of this outcome quality control is to ensure that rewards (2 points ≈ 0.03 euro, or 10 points ≈ 0.15 euro) affect participants’ performance, and thus that any other interaction (e.g. Reward by Validity) will be safely interpretable as induced by an altered motivational state.

**2.4.3.2 Effect of GVS on the SVV**

GVS is expected to tilt the SVV towards the site of anodal stimulation (Lenggenhager et al., 2007; Mars et al., 2001). We therefore predict that the LRT for GVS will be significant. We will then proceed in assessing model coefficients. No prediction is made for specific outcome configurations (e.g. Right-Anodal > SHAM, Right-Anodal > Left-Anodal, SHAM > Left-Anodal). In principle a gradient should be observed, though we adapted a clinical test to a (quick) computer-based testing and minor deviations along this pattern will be tolerated. At least one coefficient, however, must suggest that the SVV is tilted towards the anodal site (e.g., SHAM< Right-Anodal).

An effect on the SVV will confirm the effectiveness of GVS and the activation of the vestibular system, and specifically its otholitic component.

**2.4.3.3 Effect of Reward over spatial attention**

Evidence for a two-way interaction Reward by Validity (a significant LRT) would greatly ease the interpretation of any modulation given by GVS. The validity effect might be either enhanced (Bucker & Theeuwes, 2014; Munneke et al., 2015) or abolished (Engelmann et al., 2009) by rewards. The interaction and follow-up comparisons might suggest that spatial attention is more strongly attracted by exogenous cues in case rewards are attached to them, resulting in a modulation of validity gain/inhibition of return (e.g. Munneke et al., 2015). Yet, this criterion is not meant to be necessarily fatal if not met. It is in principle possible that GVS might enhance a subtle effect, leading to a meaningful modulation, although, should this case occur, caution will be taken in discussing results. Furthermore, it will still be possible to address our second question, i.e. whether the vestibular system is involved in the processing of motivational stimuli (that is the GVS by Reward interaction).

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**Study timeline**

Data collection is foreseen to last two to three months. One month will be further required for data analysis and manuscript revision. Stage 2 revisions will thus be submitted, in principle, between 3 and 4 months after stage 1.

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