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Research article

Galvanic Vestibular Stimulation Influences

Risk-Taking Behaviour

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1 **Abstract**

2   Risk-taking behaviour is an essential aspect of our interactions with the environment.

3 Here we investigated whether vestibular inputs influence behavioural measurement of risk-

4 taking propensity. We have combined bipolar Galvanic Vestibular Stimulation (GVS) with a

5 well-known and established risk-taking behaviour task, namely the *Balloon Analogue Risk*

6 *Task (BART).* A sham stimulation was used to control for non-specific effects. Left-anodal and

7 right-cathodal GVS (L-GVS), which preferentially activates the vestibular projections in the

8 right hemisphere, decreased the willingness to take risk during the BART compared with right-

9 anodal and left-cathodal GVS (R-GVS), which activates the left hemisphere. This proved a

10 *specific vestibular effect* which depends on GVS polarity. Conversely, no *generic vestibular*

11 *effect,* defined as the adjusted average of L-GVS and R-GVS conditions compared to sham,

12 emerged, excluding non-specific vestibular effects. Our results confirmed recent findings of a

13 vestibular contribution to decision-making and strategy control behaviour. We suggest that the

14 vestibular-mediated balancing of risk seeking behaviour is an important element of the brain's

15 capacity to adapt to the environment.

16

17 **Keywords**

18 Vestibular System, Risk-Taking Behaviour, Galvanic Vestibular Stimulation, Behavioural

19 Control, Balloon Analogue Risk Task.

20

21 **Abbreviations**

22 ACC   Anterior Cingulate Cortex

23 BART   Balloon Analogue Risk Task

24 GVS   Galvanic Vestibular Stimulation

25 IPL   Inferior Parietal Lobule

26 L-GVS   Left-anodal and right-cathodal Galvanic Vestibular Stimulation

27 R-GVS   Right-anodal and left-cathodal Galvanic Vestibular Stimulation

28 TPJ   Temporo-Parietal Junction

Ethics approval and consent

The experimental protocol was approved by Royal Holloway University of London research ethics committee. Consent to participate and for publication were asked to participant according to ethical standards of the Declaration of Helsinki.

Conflict of interest

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Author Contribution

G.D.M. and E.F. designed the experiment and wrote the manuscript. G.D.M collected the data. G.B. wrote the manuscript giving a critical revision of it. All Authors gave the final approval of the version to be published.

Data availability

Data are available as supplementary information.

1. Introduction

Risk is ubiquitous in human life. We make decisions in a continuously changing environment balancing expectations, internal states and possible consequences. Whenever these decisions involve potential harm or even danger, while providing the opportunity to gain rewards as a result, we talk about *risk-taking behaviour* (Leigh, 1999). Although some amount of hazardous behaviour is desirable and essential for survival and environmental adaptation, excessive risk-taking tendencies have been described in association with several clinical conditions, including compulsive gambling and drug abuse (Mishra et al., 2010; Schneider et al., 2012).

Vestibular information has been traditionally considered a specific sensory input for basic orienting behaviours, such as oculomotor adjustments, postural control, balance and gaze stabilisation (Angelaki & Cullen, 2008). The vestibular system in the inner ear comprises three orthogonal semicircular canals (anterior, posterior and horizontal) that sense rotational acceleration of the head in three-dimensional space, and two otolith organs (utricle and saccule) that jointly sense translational acceleration, including the orientation of the head relative to gravity. Human neuroimaging studies have identified several cortical areas involved in vestibular processing in the brain, including the Temporo-Parietal Junction (TPJ), posterior insula, superior temporal gyrus, Inferior Parietal Lobule (IPL), Anterior Cingulate Cortex (ACC), fronto-parietal operculum, both primary and secondary somatosensory cortices and the prefrontal cortex (Lopez et al., 2012; Eulenburg et al., 2012). This widespread vestibular cortical network is primarily located in the non-dominant right hemisphere in right-handed subjects (Dieterich et al., 2003; Duque-Parra, 2004). Notably, this unique neuroanatomical architecture suggests a vestibular contribution to cognition that goes far beyond the traditional, automatic, low-level reflex motor circuits for balance, gaze stabilisation and orientation (Ferrè & Haggard, 2020). Accordingly, artificial vestibular stimulation has been shown to modulate an impressive range of cognitive functions, including spatial attention, decision-making, body-representation, memory, motor and spatial imagery and emotion perception (Ferrè et al.,

2013a; 2013b; Ferrè & Haggard, 2020; Hilliard et al., 2019; Lenggenhager et al., 2008; Lopez et al., 2012; Miller, 2016; Pasquier et al., 2019; Preuss et al., 2017; Schmidt et al., 2013a; 2013b; Wilkinson et al., 2008).

Recent studies have demonstrated that vestibular signals play an important role in behavioural control strategy, influencing the balance between novel and routine responses in implicit decision-making tasks (Ferrè et al., 2013a, 2013b). Bipolar Galvanic Vestibular Stimulation (GVS) was used to non-invasively stimulate the vestibular organs (Fitzpatrick and Day, 2004). An anode and cathode were placed on the left and right mastoid, or vice versa. Perilymphatic cathodal currents are known to depolarize the trigger site and lead to excitation, whereas anodal currents hyperpolarize it resulting in inhibition (Gensberger et al., 2016; Goldberg et al., 1984; Minor & Goldberg, 1991). Galvanic currents equally affect the afferents innervating all five vestibular endorgans resulting in a change in the vestibular nerve afferent discharge. GVS results in a diffuse activation of the cortical and subcortical vestibular projections (Fitzpatrick & Day, 2004). Neuroimaging evidence has shown that left-anodal and right-cathodal GVS caused a unilateral activation of the right hemisphere vestibular projections, while the inverse polarity activated both left and right hemispheres (Fink et al., 2003). We have observed polarity-specific effects in a decision-making task: left-anodal and right-cathodal GVS, which primarily activates the right hemisphere vestibular projections, increased novel responses compared to right-anodal and left-cathodal GVS (Ferrè et al., 2013a, 2013b).

However, it remains unclear whether vestibular information might also modulate the willingness of taking risks. Here we have combined bipolar GVS with a well-known and established risk-taking behaviour task, namely the *Balloon Analogue Risk Task* (BART) (Lejuez et al., 2002, 2003). The BART has been widely used to implicitly measure the behavioural measurement of risk-taking propensity in adolescents (Lejuez et al., 2003), drug abusers (Campbell et al., 2013; Canavan et al., 2014), brain-injured patients (Balagueró et al., 2016) and psychopathic inmates (Swogger et al., 2010). Neuroimaging studies described

1 activations of ACC, medial-frontal cortex and dorsolateral-frontal cortex, and insula when

2 participants were asked to perform the BART (Li et al., 2020; Schonberg et al., 2012). We

3 have therefore hypothesized that GVS might induce a polarity-specific modulation of risk-

4 taking behaviour during the BART.

5

2. Materials and Methods

2.1. Participants and Ethics

8 Twenty healthy right-handed participants volunteered in the study (19 women; age

9 range 18-22 years; mean=19 years; SD=1.28 years). The sample size was estimated a priori

10 based on similar experimental procedures (Ferrè et al., 2013a; 2013b). The sample size was

11 set in advance of testing and was also used as data-collection stopping rule. Participants with

12 a history of neurological, psychiatric, vestibular or auditory disorders were excluded. Informed

13 consent was obtained prior to participation in the experiment. The experimental protocol was

14 approved by Royal Holloway University of London research ethics committee. The study was

15 designed according to ethical standards of the Declaration of Helsinki.

16

2.2. Galvanic Vestibular Stimulation

18 Bipolar Galvanic Vestibular Stimulation (GVS) was delivered using a 1mA squared

19 waveform via a commercial stimulator (Good Vibrations Engineering Ltd., Nobleton, Ontario,

20 Canada). Both mastoid processes were cleaned with surgical spirit-soaked cotton wool.

21 Carbon rubber electrodes (area ~10cm2) were then fixed binaurally with adhesive tape.

22 Electrode gel was applied to reduce skin impedance. As in our previous studies, an anode

23 and cathode were placed on the left and right mastoid, or vice versa. Left-anodal and right-

24 cathodal configuration is named L-GVS. The inverse polarity, namely right-anodal and left-

25 cathodal configuration, is named R-GVS (Figure 1A). GVS polarity-dependent differences in

26 postural, sensorimotor and cognitive functions have been demonstrated both in healthy

1 volunteers and in brain damaged patients (Ferrè et al., 2013a, 2013b; Fitzpatrick et al., 1994,

2 1999; Fitzpatrick & Day, 2004; Lenggenhager et al., 2008; Lopez, 2016; Lopez et al., 2010;

3 Oppenländer et al., 2015; Smith et al., 2010; Utz et al., 2011; Wilkinson et al., 2008, 2014).

4 These behavioural effects can be explained by the specific hemispheric cortical projections

5 activated by GVS, as demonstrated by neuroimaging studies (Bense et al., 2001; Lobel et al.,

6 1998). For example, Fink et al. (2003) found that left-anodal and right-cathodal GVS caused

7 unilateral activation of the right hemisphere vestibular projections, while the reverse polarity

8 activated both left and right hemispheres (Fink et al., 2003). A sham stimulation (SHAM),

9 based on that used by Lopez et al. (2010), was applied with a left-anodal and right-cathodal

10 electrodes configuration to the neck, 5 cm below the mastoids (Figure 1A). This causes a

11 similar tingling skin sensation, and it functions as a control for non-specific alerting effects but

12 does not activate the vestibular system and its inputs. Electrodes for L-GVS, R-GVS and

13 SHAM were placed at the beginning of the experimental session and remained in place for

14 the entire duration of the experiment. The electrodes and the polarity of stimulation were

15 selected under randomized computer control.

16

17 2.3. Experimental Procedure

18   Data from each participant was gathered in a single experimental session. Verbal and

19 written instructions about the task were given to participants at the beginning of the session.

20 To decrease the postural consequences of vestibular stimulation, the experiment was

21 conducted in a sitting position and with participant's head kept straight and steady on a

22 chinrest. This allowed avoiding any potential GVS-induced postural adjustments (Day et al.,

23 1997).

24   Participants performed the Balloon Analogue Risk Task (BART) (Lejuez et al., 2002,

25 2003) during L-GVS, R-GVS, and SHAM. These three stimulation conditions were randomised

26 between participants to control for potential order effects and the tendency to increase risky

27 behaviour as the BART progresses over time (MacLean et al., 2018). The task was

administered using PsychoPy3 (version 3.2.2; https://www.psychopy.org/). Participants looked at a computer screen (15.6" screen with 1920x1080 resolution and 60Hz refreshing rate; DELL Inspiron 15 7000 Gaming, 16GB RAM, 64bit operating system) placed in front of them at a fixed distance of 55 cm. In each trial, a red balloon was presented in the centre of the screen (Figure 1A). Participants were asked to click on a button with their right index finger to pump the balloon. Each pump gave the participants 5 pence virtual reward accumulated in a virtual temporary bank displayed on the bottom part of the screen. Participants could decide to either keep pumping the balloon to gain more virtual money while risking making the balloon explode and therefore losing the accumulated money, or click with their middle finger to virtually bank permanently the money gained for that balloon. The permanently banked amount of money was displayed on the top part of the screen. When the balloon exploded, a clearly audible bursting sound was emitted, and the phrase "*Oops! Lost that one!*" appeared on the screen. When the money was successfully collected, the sentence "*You have banked: £…*" appeared on the screen. This sentence disappeared after 1.5s and another balloon was then presented. Each trial corresponded to a balloon, and a total of 30 balloons were presented during the task. According to previous experiments, each balloon was associated with a fixed number of pumps which corresponds to its breaking point, or in other words the probability to gain a monetary reward. The number of maximum pumps varied between 1 and 128 pumps, following standard distributions (Lejuez et al., 2002, 2003) and presented in random order. Participants were instructed to try to make as much money as possible, however, no real winnings have been paid out. To get familiar with the task, participants performed a brief practice block of 5 trials. The BART was performed during each stimulation condition (L-GVS, R-GVS, SHAM). The BART was designed to last less than five minutes (average duration across participants = 3.84 min; SD = 1.17 min) to prevent a potential sensory habituation during GVS. Between each GVS/SHAM condition participants took a break of at least 5 minutes to avoid potential stimulation after-effects.

2.4 Data Analysis

The adjusted average pumps, namely the average number of pumps for the unexploded balloons (Lejuez et al., 2002; White et al., 2008), was estimated for each vestibular stimulation condition (L-GVS, R-GVS and SHAM) for each participant. To avoid anticipation responses, participants were not allowed to start pumping and/or collecting the virtual money for the subsequent balloon before the "losing" or "winning" phrase disappeared from the screen and the balloon was visually presented. Therefore, we decided to exclude responses given within this period of time (i.e. 1.5s), that were generally 0 (meaning the participant clicked to collect money without having given a single pump) or 1 (only one pump given) (excluded responses = 0.67%).

We a priori hypothesized that vestibular stimulation might influence risk-taking behaviour in two distinct ways, and we consequently tested these hypotheses as planned contrasts. First, any activation of the vestibular system might influence risk-taking behaviour independent of GVS polarity and hemispheric effects. For instance, a pure arousal account would predict changes in behavioural tasks independently from the GVS polarity. To test this *generic vestibular effect* hypothesis, we compared the adjusted average pumps for the L-GVS and R-GVS conditions to the SHAM condition. Second, we hypothesised that the effects of vestibular stimulation might be specific and related to the hemisphere mainly activated by GVS. In fact, several studies reported different effects induced by L-GVS and R-GVS in both neurological patients and healthy volunteers (see for a review Utz et al., 2010). To test the *specific vestibular effect* hypothesis we directly compared L-GVS and R-GVS conditions. Paired t-tests were conducted using both frequentist and Bayesian approaches using JASP (version 0.9.2) (JASP Team, 2019). Bayes factors were calculated using the default Cauchy prior distribution with a scale factor of 0.707.

2.5 Data Accessibility

Supporting data are available as Supplementary Material.

==================== **PLEASE INSERT FIGURE 1 HERE** ====================

3. Results

The proportion of exploded balloons in each GVS condition was numerically similar (L-GVS = 0.24, SD = 0.12; R-GVS = 0.28, SD = 0.15; SHAM = 0.29, SD = 0.16) ruling out a potential impact of the exploded balloons on subsequent choices made by participants.

First, we investigated whether any activation of the vestibular system might influence risk-taking behaviour independently of GVS polarity and hemispheric effects, perhaps because of non-vestibular effects such as changes in general arousal. Thus, the *generic vestibular effect*, defined as (L-GVS + R-GVS)/2 (mean number of pumps =23.25; SD=9.723), was compared to the SHAM condition (mean number of pumps =26.03; SD=12.103). This analysis revealed no significant differences (t=-1.715; df=19; p=0.103; Cohen's d=0.384) (Figure 1B). In addition, a low Bayes factor was estimated (BF10=0.83; Posterior Median=0.334; 95% CI: [-0.084, 0.787]), indicating no evidence in favour of either H1 or H0. Taken together these results suggest no support for a generic vestibular effect on risk-taking behaviour.

We next compared L-GVS (mean number of pumps =21.23; SD=10.37) and R-GVS (mean number of pumps =25.27; SD=10.42) conditions to investigate the effects of vestibular stimulation specific to the hemisphere activated (specific vestibular effect). This analysis revealed a significant difference (t=-2.451; df=19; p=0.024; Cohen's d=-0.548) (Figure 1C). Bayes factor showed a moderate index (BF10=4.893; Posterior Median=-0.484; 95% CI: [-

1   0.947, -0.090]) in favour of H1 over H0. These results suggest a polarity-specific effect:

2   compared to right-anodal and left-cathodal GVS, left-anodal and right-cathodal GVS caused

3   a reduction in the number of pumps in the BART. In other words, L-GVS triggered a change

4   in decision-making strategies towards less risky choices.

5   **4. Discussion and conclusion**

6   Successfully dealing with risks is a fundamental aspect of human adaption to the

7   surrounding environment. Here we show that vestibular input, in general, did not modulate the

8   cognitive processes involved in risk-taking propensity. However, specific polarities of

9   vestibular input, associated with activation of vestibular projections in each hemisphere

10   separately, had differential effects on risk-taking behaviour. In particular, L-GVS induced a

11   significant reduction in risk tendencies compared to R-GVS. That is, during left anodal and

12   right cathodal GVS, which primarily activates the vestibular areas in the right hemisphere,

13   participants adopted more conservative strategies in evaluating the probability to gain or lose

14   a virtual monetary reward.

15   Our results confirmed recent findings of a vestibular contribution to decision-making

16   and strategy control behaviour. Preuss and colleagues (Preuss et al., 2014) have described a

17   vestibular influence on one's desirability to buy a product in economic decision-making tasks.

18   Further, left-anodal and right-cathodal GVS has also been shown to influence heuristics

19   involving emotional context and framing susceptibility in risky choice games (Preuss et al.,

20   2014, 2017). In particular, left-anodal and right-cathodal GVS increased the willingness to take

21   risks when the focus of the framing was given to potential losses while it decreased risk-taking

22   behaviour when the focus was on potential gain (Preuss et al., 2017). In our study, participants

23   were asked to decide whether to keep pumping the balloon to gain a monetary reward while

24   increasing the risk of making the balloon explode and therefore losing their potential reward,

25   or refrain to risk for a larger reward. According to Preuss and colleagues (2017), the observed

26   decrease in risk-taking behaviour induced by left-anodal and right-cathodal GVS could be

11

1 potentially related to the conceptual framing of the BART which focuses on the reward rather

2 than loss (i.e., participants are explicitly instructed to try to make as much money as possible).

3 Left-anodal and right-cathodal GVS might have therefore modulated the perceived desirability

4 of the reward. Interestingly, in decision-making tasks in which neither reward nor risk is

5 involved, left-anodal and right-cathodal GVS increased the proportion of novel responses, and

6 right-anodal and left-cathodal GVS promoted routine stereotyped ones (Ferrè et al., 2013a,

7 2013b). Importantly, taken together these results support a functional interaction between

8 vestibular signals and high level cognitive processes involved in behavioural control.

9 Polarity-dependent GVS effects have been observed both in brain-damaged patients

10 and in healthy participants (Utz et al., 2010). Here we report a polarity spec*ific vestibular effect*

11 in risk-taking behaviour. Neuroimaging studies have identified an asymmetry in the cortical

12 vestibular network, suggesting a right hemisphere dominance in right-handed participants

13 (Bense et al., 2001; Dieterich et al., 2003; Janzen et al., 2008; Suzuki et al., 2001). Thus, the

14 observed hemispheric-specific effects in risk-taking propensity might arise because of this

15 cortical asymmetry, or because one polarity of GVS has stronger effects in the brain. We

16 suggest that the difference between left-anodal and right-cathodal GVS and right-anodal and

17 left-cathodal GVS in hazardous decisions may be caused by changes in cortical excitability in

18 widespread hemispheric networks for behavioural control. Brown and Braver (Brown & Braver,

19 2007) have shown a strong hemispheric specialization in behavioural control: the right

20 hemisphere ACC, temporal gyrus, and middle/superior frontal gyrus are selectively involved

21 in preventing errors, minimising losses, and predicting adverse outcomes. Similarly, activation

22 of the right ACC and insula have been observed when people were taking risks during the

23 BART (Li et al., 2020; Schonberg et al., 2012). Importantly, these regions are also core areas

24 receiving vestibular projections and might be therefore good candidates for subserving the

25 observed vestibular modulation of risk-taking behaviour. The sudden artificially-induced

26 activation of these areas might have triggered changes in the overall cortical excitation, which

12

1 might have been reflected in behavioural changes, such as an increase of risk-averse choices

2 and therefore more conservative responses.

3   Our willingness to take risks is often influenced by the actual or even perceived value

4 of the reward. For instance, Bornovalova and colleagues (Bornovalova et al., 2009) highlighted

5 how hazardous tendencies were dramatically reduced as the reward/loss ratio (e.g., the pay-

6 out) increased, suggesting that decision-making is intrinsically influenced by the awareness of

7 potential losses. Accordingly, people with higher impulsivity have been shown to be much less

8 susceptible to the reward/loss ratio. Importantly, several studies have highlighted differences

9 in behavioural responses when participants were presented with a real vs. hypothetical reward

10 during the BART. In particular, the real pay-out induced a reduction in risk-taking behaviour

11 compared to a virtual scenario (Xu et al., 2016), similar to the one used in the present study.

12 Left-anodal and right-cathodal GVS might have altered the perceived trade-off between gains

13 and losses towards less hazardous strategies. Changes in motivation might account for our

14 findings and potentially provide an explanation that does not directly involve decision-making.

15 However the two accounts might not necessarily be mutually exclusive and since no real-life

16 monetary reward was given here, it is unlikely that the changes induced by left-anodal and

17 right-cathodal GVS are merely driven by motivation.

18   It has been largely reported that artificial vestibular stimulation influences spatial

19 attention (Utz et al., 2011). Attentional shifts of attention towards one side of the personal

20 and/or extra-personal space have been observed in neurological patients and healthy

21 participants (Dilda et al., 2012; Kerkhoff, 2001; Rorsman et al, 1999; Utz et al., 2011). For

22 example, left anodal and right cathodal GVS induced a leftward attentional bias, while right

23 anodal and left cathodal GVS reversed this bias, in a bisection task (Ferrè et al., 2013). Thus

24 one might argue that the hemispheric effect in risk-taking behaviour might be driven by

25 attention mediated mechanisms, for instance, a preference in pressing the left or right button.

26 However, our data do not fully support this account. An attentional driven effect would have

27 caused a L-GVS preference towards the leftmost button, which in our task corresponded to

the 'inflate the balloon' key. Thus, a completely opposite pattern of results should have been observed. Further, recent studies excluded a direct influence of GVS on motor effectors (Abekawa et al., 2018; Ferrè, Arthur, et al., 2013).

Artificial vestibular stimulation may also influence emotional responses and anxiety levels (Pasquier et al., 2019; Sailesh et al., 2016). Critically, anxiety levels may influence risk-seeking behaviour during the BART (Lighthall et al., 2009). Therefore, one might speculate that the observed changes in risk-taking measures are indirect anxiety-driven, rather than directly vestibular modulations. However, an account based on indirect anxiety driven changes cannot fully explain our results. First, previous studies have shown changes in anxiety levels only after prolonged GVS exposure (for example 38 or 78 minutes GVS for 3 sessions in Pasquier et al. 2019; 146 ± 5.6 days GVS in Sailesh et al. 2016). In our study, GVS lasted less than a few minutes in each block (max. 4.86 minutes). Second, an account based on indirect vestibular effects based on changes in anxiety would have predicted differences in risk index between SHAM and vestibular conditions (i.e. generic vestibular effect), which we did not observe. Finally, in our knowledge, no evidence has so far supported GVS polarity-specific changes in anxiety.

In conclusion, our results showed polarity-dependent effects of GVS on risk-taking behaviour. We suggest that the vestibular-mediated balancing of risk-seeking behaviour is an important element of the brain's capacity to adapt to the environment.

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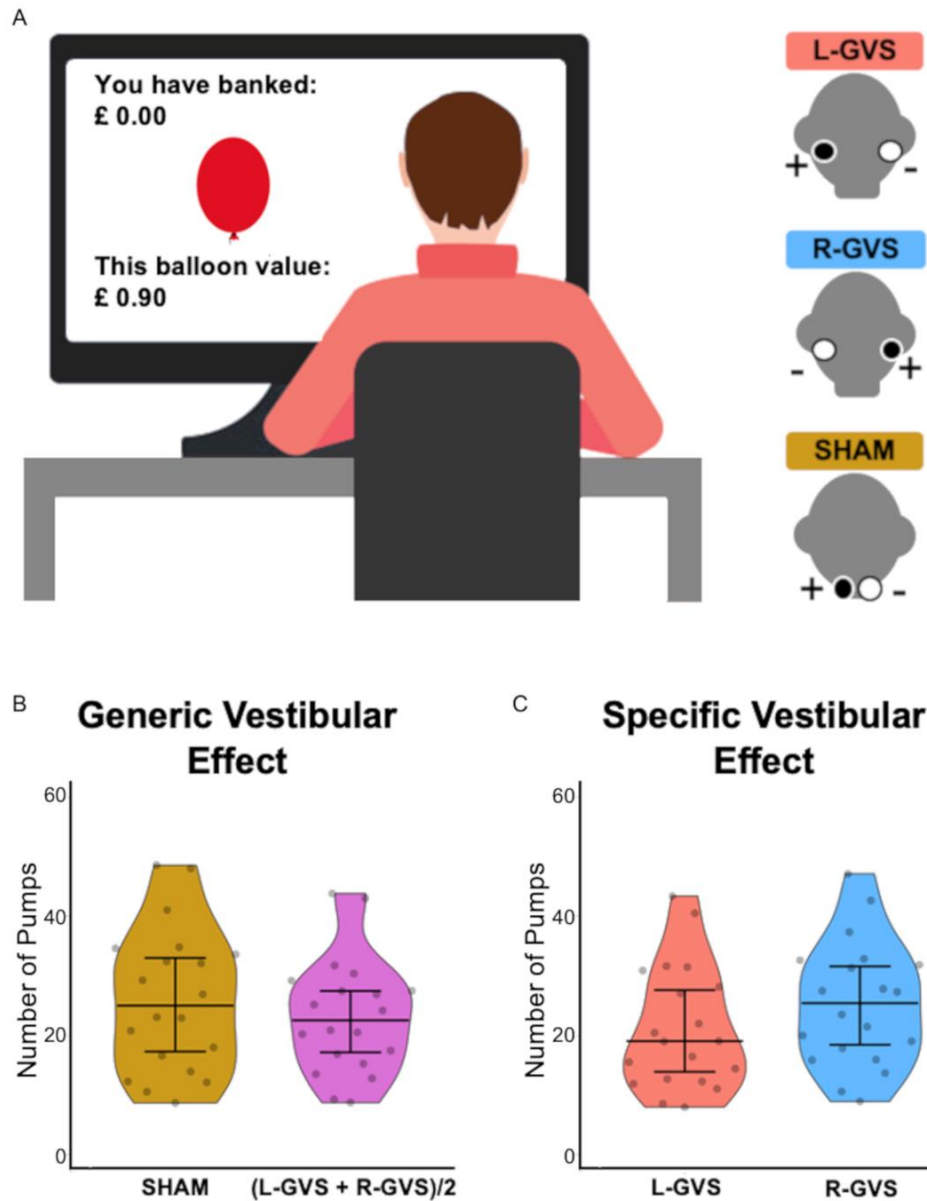
Figure 1. Effects of GVS on risk-taking behaviour.

(A) Experimental set-up and GVS electrodes configurations. (B) No differences emerged in the number of pumps between SHAM and the average of L-GVS and R-GVS. (C) L-GVS reduces the number of pumps, and therefore risk-taking behaviour, compared to R-GVS.