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Allocating less attention to central vision during vection is correlated with less motion sickness

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ABSTRACT

Visually induced motion sickness (VIMS) is a common discomfort response associated with vection-provoking stimuli. It has been suggested that susceptibility to VIMS depends on the ability to regulate visual performance during vection. To test this, 29 participants, with VIMS susceptibility assessed by Motion Sickness Susceptibility Questionnaire, were recruited to undergo three series of sustained attention to response tests (SARTs) while watching dot pattern stimuli known to provoke roll-vection. In general, SARTs performance was impaired in the central visual field (CVF), but improved in peripheral visual field (PVF), suggesting the reallocation of attention during vection. Moreover, VIMS susceptibility was negatively correlated with the effect sizes, suggesting that participants who were less susceptible to VIMS showed better performance in attention re-allocation. Finally, when trained to re-allocation attention from the CVF to the PVF, participants experienced more stable vection. Findings provide a better understanding of VIMS and shed light on possible preventive measures.

Practitioner Summary: Allocating less visual attention to central visual field during visual motion stimulation is associated with stronger vection and higher resistance to motion sickness. Virtual reality application designers may utilise the location of visual tasks to strengthen and stabilise vection, while reducing the potential of visually induced motion sickness.

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KEYWORDS
Visually induced motion sickness; motion sickness susceptibility; vection; visual attention

Introduction

In recent years, virtual reality (VR) technology has been successfully applied in many areas (Riecke 2011) including education (Wickens 1992; Moskaliuk, Bertram, and Cress 2013), medical treatment (Bouchard 2011; Parsons and Cobb 2011) and manufacturing (Hsiao et al. 2005; Ganier, Hoareau, and Tisseau 2014). Large visual moving scenes are able to provide a vivid illusion of self-motion (vection) and thus strengthen the user experience and effectiveness of VR (Riecke et al. 2004; Riecke 2011). Owing to this, performing visual tasks while exposure to vection-inducing moving background has become increasingly common in VR applications, such as video games (Menache 2011; Caroux, Bigot, and Vibert 2013) and safety trainings (Meng and Zhang 2014).

However, one major concern regarding this type of complex and dynamic visual interface is that it can lead to visually induced motion sickness (VIMS). Prolonged exposure to vection provoking stimuli in VR environments often introduce VIMS, typically reported with symptoms including disorientation, oculomotor disturbances and gastrointestinal discomfort (Miller and Graybiel 1974; Golding 1998). Although modifying the properties of visual stimuli can reduce VIMS, those methods usually also hurt the vection experience (Stern et al. 1990; Golding et al. 2012; Bonato, Bubka, and Thornton 2015). Notice that, the susceptibility to VIMS actually varies a lot in the population, with about one-third of the viewers relatively resistant to VIMS when experiencing vection (Stanney, Kingdon, and Kennedy 2002; Griffin 2012; Chen et al. 2015). Thus, by exploring why some people can be resistant to VIMS might provide a possible breach. At the ISO Workshop Agreement held in Tokyo in 2005, experts concluded that more studies were needed to determine the factors related to VIMS susceptibility (IWA, 2005).

VIMS susceptibility and visual response regulation

Among several theories explaining the origin of VIMS, 'sensory conflict theory' (Reason 1978) is widely believed to be the most promising. Although 'sensory conflict' has been

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criticised as unmeasurable (Griffin 2012), recent advances in brain imaging have led to increasing neurological evidence supporting the theory (Deutschländer et al. 2002; Chen et al., 2009; DeAngelis and Angelaki 2012; Keshavarz et al. 2015; Zhang et al. 2015). According to sensory conflict theory, vection-inducing stimuli introduce conflicts primarily between the visual and vestibular systems – the two major modalities responsible for the perception of self-motion. These conflicts then lead to mismatched neural activities and trigger VIMS.

As the sensory conflict theory does not address the issue of the large variations in VIMS susceptibility across individuals, Brandt extended and complemented this theory by introducing a conflict-reducing mechanism, the reciprocal inhibitory interaction between the visual and vestibular systems (Brandt et al. 1998, 2002). This mechanism facilitates negative regulation on the vestibular system and positive regulation on the visual system during vection resulting in effective reduction of conflicting self-motion neural signals. Accordingly, VIMS susceptibility has been hypothesised as a failure to implement this mechanism. In support of the hypothesis for visual response regulation, it has been reported that when individuals are exposed to vection-inducing stimuli, their neurological responses associated with visual activities increase compared with controls (Bense et al. 2001; Brandt et al. 2002; Della-Justina et al. 2014; Keshavarz and Berti 2014). Yet, other studies have argued that visual responses are suppressed (both behaviourally and neurologically), not activated, when individuals experience vection (Kleinschmidt et al. 2002; Thilo, Kleinschmidt, and Gresty 2003; Stróżak et al. 2016). Based on Brandt's theory (1998), individual VIMS susceptibility should depend on the strength of visual-vestibular reciprocal regulation of the person. Therefore, we expect the visual response regulation during vection to vary according to individual VIMS susceptibility.

Unfortunately, none of the studies reviewed above reported the VIMS susceptibility of their participants. Consequently, it is still unclear whether the inconsistent visual regulation during vection was caused by different levels of VIMS susceptibility or other factors. As such, it is necessary to further explore the regulation of visual response among individuals with different levels of VIMS susceptibility.

Functional difference in central vs. peripheral vision

To study visual response regulation during vection, it is important to consider the functional differences between central and peripheral vision. The human visual system is a complicated mega system that simultaneously fulfils many more functions than self-motion perception alone (Zeki 1990). In general, the peripheral visual field (PVF) contributes more to the 'where' function (e.g. location and motion) (Dichgans and Brandt 1978; Agyei et al. 2015; Uesaki and Ashida 2015) and the central visual filed (CVF) is more devoted to the 'what' function (e.g. colour, contrast and object recognition) (Zeki et al. 1991; Ungerleider 1994; Wandell, Brewer, and Dougherty 2005). Hence, Brandt's visual response regulation should not apply evenly to the whole visual field; instead it affects the PVF and the CVF differently, since the PVF rather than the CVF is primarily responsible for providing self-motion cues (Dichgans and Brandt 1978; Ungerleider 1994). Moreover, previous experiments have also suggested that the PVF and CVF play different roles in generating vection and VIMS (Webb and Griffin 2003).

In summary, it can be inferred that visual response regulation in the PVF and the CVF are different during vection. However, most previous investigations on visual response under vection-inducing stimulation have either adopted tasks that only reflect effects in the CVF (e.g. Thilo, Kleinschmidt, and Gresty 2003; Menozzi and Koga 2004; Stróżak et al. 2016), or applied measures that yielded inseparable effects from the PVF and CVF (e.g. Brandt et al. 1998, 2002; Bense et al. 2001; Kaminiarz, Krekelberg, and Bremmer 2007; Caroux, Bigot, and Vibert 2013). Therefore, new measures separating the PVF and CVF are needed. Moreover, it is important to find a new objective predictive measure of VIMS susceptibility without making the subjects sick (Hu et al. 1989; Guo et al. 2017). Since the visual response regulation varies with VIMS susceptibility according to Brandt et al. (2002), exploring it could potentially uncover new objective measures of VIMS susceptibility.

One promising candidate test for investigating the visual response regulation during vection is the Sustained Attention to Response Test (SART). As a valid and frequently used measure of sustained visual response (Van Schie et al. 2012; Head et al. 2013; Dillard et al. 2014), SART can reflect the sustained attention assigned to a particular visual location (Robertson et al. 1997; Manly et al. 1999). This is very useful for separating and comparing the visual response in different visual locations (PVF vs. CVF). Moreover, SART can be conducted superimposed on other visual stimuli (Dillard et al. 2014), hence it is applicable to be assessed simultaneously with vection perception. Finally, performance in SART is measured by response time and accuracy (Manly et al. 1999), which can be obtained from quick and simple paradigms (Robertson et al. 1997; Manly et al. 1999).

Motivation for the current study

As mentioned before, the current trend in VR technology calls for more investigations on visual response regulation during vection and its association with VIMS

susceptibility. Specifically, this study test SART under vection-inducing stimulation among participants with various degree of VIMS susceptibility. As the roll axis rotation has been reported to induce stronger motion sickness than other type of movements (Diaz-Artiles et al. 2016; Van Ombergen et al. 2016), we presented a coherent rotating dot pattern to introduce roll vection and examined the changes in SART performance in the PVF and CVF during vection. Brandt et al. (1998) also used similar stimuli. In Experiment 1a (Exp.1a), static targets were used for SART, while in Experiment 1b (Exp. 1b) we adopted targets rotating at five different speeds to further examine the properties of visual response regulation effects. Furthermore, to better facilitate and guide VR applications, a follow-up Experiment 2 (Exp. 2) was conducted to explore whether subjects can be trained to regulate their visual response, and how vection perception was affected. All procedures were approved by the university ethics committee and performed in accordance with the Declaration of Helsinki.

Experiment 1a

Based on Brandt's theory (2002), visual response regulation could be considered as a means to improving visual performance and facilitating sensory conflict reduction during vection. As explained above, regulation on visual response is expected to be mainly directed towards self-motion cues in the PVF. We hypothesised that the influence of visual response regulation on SART performance in the presence of vection depends on whether the visual targets are in the PVF or CVF (H1). In particular, we expect vection to be associated with improved SART performance in the PVF (H1a) and weakened performance in the CVF (H1b). Moreover, as visual response regulation is supposed to be part of the 'sensory conflict' reduction mechanism, the individual effect would vary depending on VIMS susceptibility (H2). Preliminary data from Exp. 1a have been presented at the 2017s Annual Meeting of the Chartered Institute of Ergonomics and Human Factors held in the United Kingdom (Wei, Fu, and So 2017).

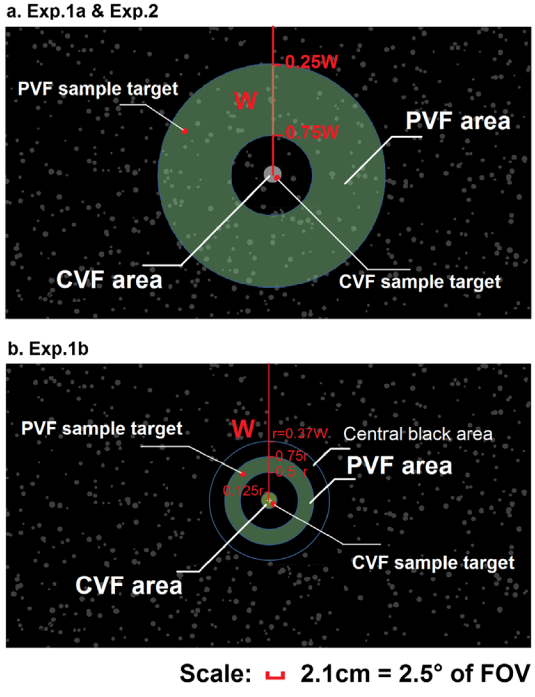

Figure 1. Illustration of the stimuli and target positions.
Notes: *W* indicates the half length of screen vertical width; *r* indicates the radius of central black area in Exp.1b; Green shadow is only for illustration of CVF/PVF areas and was not presented in actual stimuli; target diameter is 0.53 cm in Exp.1a and 1.06 cm in Exp.1b; target luminance: 5.86 cd/m^2 for red disc and 10.80 cd/m^2 for green disc.

Methods

Participants

Fourteen right-handed university students (8 male; Age: 19–27 years old, mean 23.31, SD 2.02), who were free of vestibular injury or medical treatment, with 20/20 (or corrected) eyesight and normal colour vision, were recruited with complete informed consent. A large variation in VIMS susceptibility (measured with the Motion Sickness Susceptibility Questionnaire (MSSQ) Short-form; see Golding 1998) was ensured in this group of participants, which basically follows the percentile distribution in the population (See Appendix 1).

Apparatus and stimuli

A rotating dot pattern (Figure 1a) was presented on a 46-in LCD monitor with a view distance of 48 cm, occupying 93.5° × 61.8° in the field of view (FOV) to provoke roll vection. Grey dots (luminance: 0.27 cd/m^2; contrast: 58.8%; FOV diameter: 0.5~1.3°) were randomly generated on a black background (luminance: 0.07 cd/m^2). To investigate the visual response regulation associated with vection rather than local motion or visual complexity, two types of stimuli were designed: coherently rotating stimuli (CRS) and incoherently rotating stimuli (IRS). For CRS, all dots rotated anticlockwise coherently around the centre of the LCD screen at 32°/s. For IRS, each dot had a different centre of rotation and the dots were randomly distributed inside a central window (size: 33.3° of FOV). They had the same angular velocity as dots in CRS and the radius was similarly distributed. During the whole experiment (Exp), the dot pattern was randomly distributed on a canvas larger than the screen window, with 600~650 dots visible during each moment. Parameters of stimuli were chosen based on our pilot study and previous findings (Chen et al. 2015; Zhao 2017).

A grey disc (FOV size: 5°) was presented at the centre of the screen as the fixation marker. All participants were

trained to fix their eyes on the disc to suppress optokinetic nystagmus (OKN) (Wyatt et al. 1995; Ji, So, and Cheung 2009) and control other types of eye movement. Eye movement was monitored using an eye tracker (Eyetech, TM3) in a separate session to ensure that participants were able to keep their eyes on the fixation marker during the experiment for most of the time. The visual stimuli were programmed with MATLAB incorporated with Psychtoolbox-3.

Procedures

The commonly applied SART paradigm (Manly et al. 1999) was used to explore visual response regulation in the PVF and CVF. During a typical SART, a series of targets would appear sequentially during a time period called block. The appearance of each target is called a trial, while subjects should respond to a common target and withhold their response to a rare target. In this study, for each trial, one target (red/green disc, randomised at a ratio of 4/1) was presented on the screen and kept static for 500 ms. The interval between two successive trials was randomised in the range 1000~1500 ms so that subjects would not be able to predict the appearance of a target. Subjects were instructed to press a response button as soon as they saw the red disc and do nothing when the green disc appeared. The SART performance of subjects under CRS and IRS conditions was examined. To compare the effects in the PVF and CVF, targets would randomly appear either inside the foveal central area (FOV: 0~2.1°) or in the peripheral area (FOV: 7.9°~24.9°; see Figure 1a) (Webb and Griffin 2003; O'Connell et al. 2017). Total 200 trials were divided into two blocks. In each block, fifty repetitions of the SART trial were conducted for each target location (CVF and PVF) under one type of stimulus condition (CRS or IRS). Target location were randomised in each block (half CVF and half PVF), while the order of blocks was randomised for subjects.

All subjects received sufficient training on SART and vection onset judgement before taking part in the actual experiment. Throughout the whole experiment, subjects were required to conduct the SART with their left hand, while pressing another vection report button with their right hand to indicate a change in their perception state (i.e. whether experiencing vection or not). SART Trials completed under CRS during the period of vection perception were kept as valid vection trials, while trials completed under IRS during the period of no vection perception were kept as valid control trials. Similar to previous studies, trials conducted within 2 s of a change in perception state were excluded to eliminate the influence of an intermediate state (Kleinschmidt et al. 2002). Total percentage of valid trials was over 88% with no significant differences across blocks. To validate the manipulation of vection strength in the two stimulus conditions (CRS vs. IRS), subjects were trained to report vection intensity after each block based on a 5-point vection magnitude scale revised from previous studies (1 = no vection; 5 = saturated vection; Webb and Griffin 2003). To ensure SART performance was not impeded by VIMS symptoms, the block exposure time was kept short (<3 min) with sufficient rest between blocks. We used a chinrest to restrict head and body movement. To reduce environmental influences, ceiling lights were switched off, earplugs were used and a black curtain was used to cover the monitor and the head of subjects.

Dependent measures

Response time (RT) of each type of condition was calculated by averaging corrected valid responses made within 200~1500 ms after the onset of target. The accuracy of each condition was calculated by dividing the number of corrected responses by the total number of valid trials. VIMS susceptibility data of all participants were assessed using MSSQ Short-form (Golding 1998), which has been widely adopted and shown to be a proper indicator of VIMS susceptibility (Zhao 2017). The score of the child scale and that of the adult scale were calculated, while adding up the two scores yielded the total score.

Results

A repeated measures MANOVA (RMANOVA) was conducted for each of RT and accuracy, with vection (vection or control trials) and visual location (CVF or PVF) as within-subject factors and individual MSSQ-Short scores (MSSQ_C for the child scale and MSSQ_A for the adult scale) added as two covariates in the model. Interaction effect of vection × location was found to be significant both for RT [$F(1,11) = 16.715$, $p = 0.002$] and accuracy [$F(1,11) = 22.204$, $p = 0.001$], showing different patterns of performance for the PVF and CVF during vection from those of the controls (supporting H1; see Figure 2a). Moreover, the interaction terms of vection × MSSQ_C [$F(1,11) = 7.614$, $p = 0.019$] and vection × location × MSSQ_A [$F(1,11) = 4.919$, $p = 0.049$] were also significant for RT (supporting H2). For all comparisons, significant changes in RT were found in accordance with accuracy, which ensures the effects were not due to a speed-accuracy trade off. Also, the main effects of location were significant both for RT and accuracy ($p < 0.001$), where subjects generally reacted more quickly and accurately in the CVF than the PVF.

Effects in the PVF

In the PVF, further simple effect analysis showed that SART performance was improved with vection, both for RT [$F(1,11) = 3.628$, $p = 0.083$] and accuracy [$F(1,11) = 11.0$, $p = 0.001$] (supporting H1a). Note that the simple main vection effect of RT is only marginally significant, possibly due to the significant interaction between vection × MSSQ_A

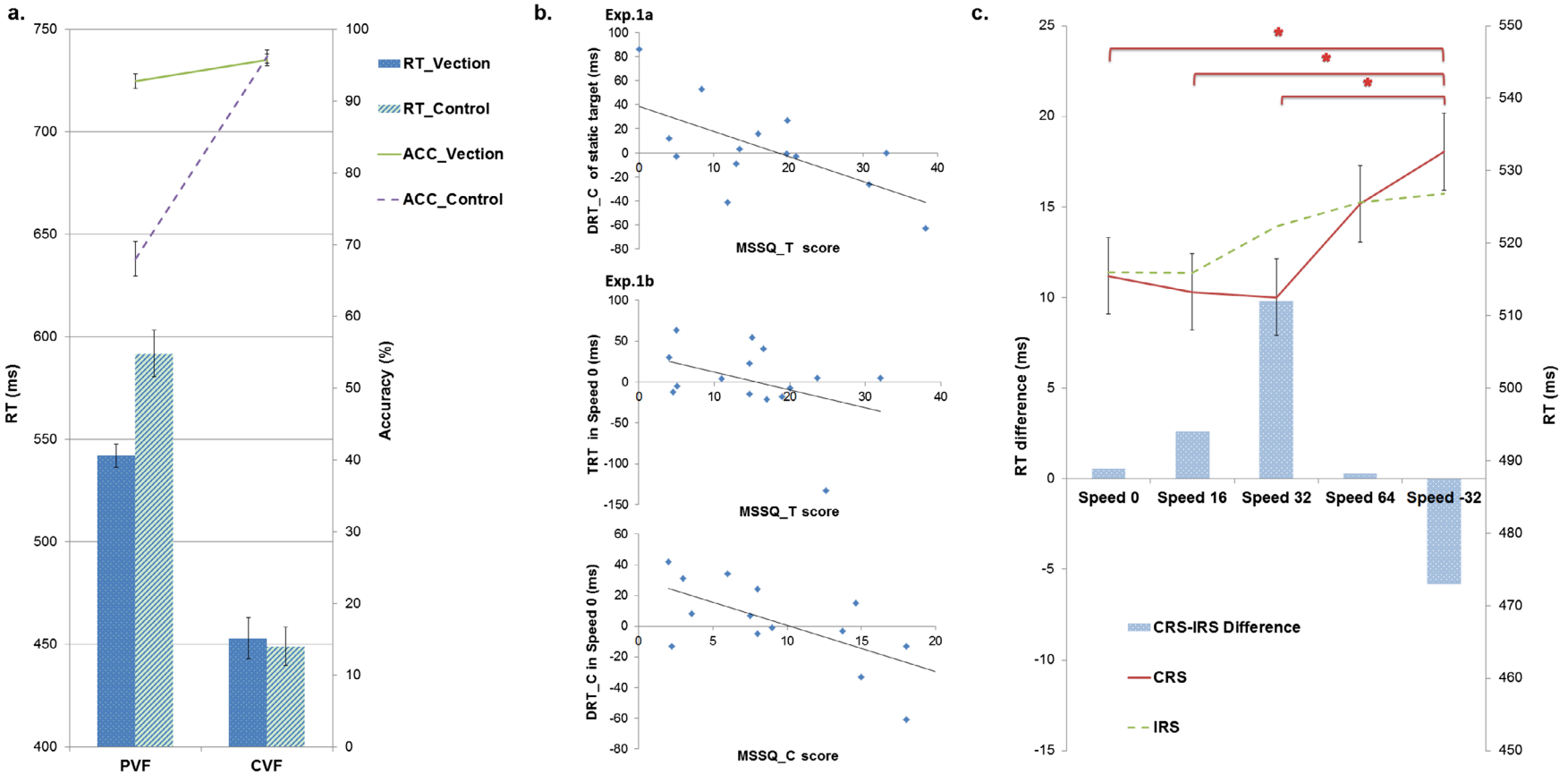

Figure 2. Effects of visual response regulation reflected in Exp. 1a and Exp. 1b and their correlation with MSSQ scores illustrated in scatter plots.

Notes: (a) Interaction effect of vection and visual location on SART performance in Exp.1a; note that the effect direction of RT in CVF is subjected to individual MSSQ scores (check Figure 2b); Acc = Accuracy; *_vection = averaged from vection trials in CRS condition; *_control = averaged from control trials in IRS condition; (b) Correlation of RT effects and MSSQ scores illustrated by scatter plots; MSSQ_T = MSSQ total scale; MSSQ_C = MSSQ child scale; TRT = total effect; DRT_C = delay of RT in CVF; (c) The modulation of strong vection on RT for target moving at different speed in Exp.1b; notice that there is no significant difference across all speed under IRS condition.

[F(1,11) = 4.884, p = 0.049], which showed a larger RT improvement for subjects with smaller MSSQ_A scores (supporting H2). No significant interaction term was found for accuracy.

Effects in the CVF

In the CVF, the RT performance in the SART was impaired during vection [F(1,11) = 8.895, p = 0.012]. Moreover, not only the magnitude but also the direction of the CVF effect was different from those of the PVF effect (see Figure 2a, supporting H1b). The interaction term of vection × MSSQ_C [F(1,11) = 7.691, p = 0.018] is also significant, which suggests a larger delay in response for subjects with smaller MSSQ_C scores (support H2). No significant effect was found for accuracy.

Correlation of effect magnitudes and MSSQ scores

Since the interaction between SART performance and MSSQ was only found for RT, we focused on RT and further analysed whether individual RT changes are correlated with MSSQ scores. To quantify the magnitude of individual effect in the PVF, a decrease in RT in the PVF (DRT_P) was calculated as RT (ms) of controls minus the RT during vection. Note that effects in the CVF is opposite to effects in the PVF, so we used the delay in response in the CVF (DRT_C), calculated as the RT during vection minus the RT of controls, while the total RT effect (TRT) was calculated by combining DRT_P and DRT_C. Pearson correlations between MSSQ-Short scores (total, child and adult scales: MSSQ_T, MSSQ_C, MSSQ_A; a higher score indicates a higher VIMS susceptibility; see Golding 1998) and the indicators of effect magnitude (DRT_P, DRT_C and TRT) were negative (see Table 2 for coefficients and p-values; see Figure 2b for scatter plots).

Vection and nausea report

Reported vection intensity and duration were significantly stronger and longer under CRS than IRS (See Table 1). No participants experienced nausea, vomiting or other severe discomfort.

Table 1. Vection report in Experiments 1a and 1b.

Vection indicators	Exp. 1a			Exp. 1b		
	CRS	IRS	T/Z-value*	CRS	IRS	T/Z-value*
Intensity	2.54 (0.96)	1.50 (0.52)	4.315 (p = 0.001)	2.62 (0.40)	1.76 (0.62)	6.194 (p < 0.001)
Duration#	8.83 (1.30)	0.72 (1.15)	15.116 (p < 0.001)	7.12 (1.99)	2.54 (2.68)	6.314 (p < 0.001)
Occurrence ratio^	14/14	7/14	2.449 (p = 0.014)	15/15	10/15	2.236 (p = 0.025)

*Paired T-test was conducted for intensity/duration; Wilcoxon signed-rank test was conducted for vection occurrence, with Z-value reported.;

^The occurrence ratio represents the number of subjects reporting vection to the total number of subjects.

#For Exp. 1a, vection duration was calculated as the length of vection time period divided by the total length of time and transformed into an 11-point scale (see Exp. 1b) to facilitate comparison.

Discussion

Results support hypothesis H1 that vection and visual location of targets have significant interaction effects on SART performance. More specifically, data indicate that vection perception is associated with improved SART performance in the PVF and impaired performance in the CVF. Since SART usually reflects sustained visual attention or vigilance (Manly et al. 1999), our results suggest that more attention is directed towards the PVF than the CVF during vection. This finding is consistent with a former study that reported a delayed response of the oddball task in the CVF during horizontal vection (Stróżak et al. 2016). As the total attention resource for visual information processing is limited (Kahneman, 1973; Marois & Ivanoff, 2005), assigning more resource to the PVF for processing self-motion cues could result in less resource directed towards the CVF and thus impaired performance in this field. This difference in changes during vection is consistent with Brandt et al.'s (2002) hypothesis about visual response regulation under vection-induced stimulation.

Furthermore, correlations between MSSQ scores and SART performance levels suggest that these effects vary according to VIMS susceptibility (H2). Data indicate that effect in the PVF is associated with the MSSQ adult scale, while effect in the CVF is closely associated with the child scale (Table 2). As the child scale can be used as a pre-morbid indicator of motion sickness susceptibility in patients with vestibular disease (Golding 1998), a closer examination of SART in the CVF might lead to useful new assessment tools for clinical consideration. Further correlation analysis showed that the magnitude of visual response regulation is greater for participants who are less susceptible to VIMS, which is consistent with Brandt's theory (1998, 2002). It is worth noting that the effects measured in the CVF showed better predictive power for MSSQ scores (DRT_P is only marginally significant), possibly because improvements in PVF performance had reached the ceiling for most of the subjects (see Figure 2a). In addition, as SART targets in the PVF were superimposed on the background with a random dot pattern that possessed a higher visual complexity than the central grey disc (see Figure 1a), the visual performance might also be affected by background visual complexity (Caroux, Bigot, and Vibert 2013). More investigations controlling for this confounding factor are desirable.

Experiment 1b

Experiment 1b (Exp.1b) is a follow-up experiment designed to explore in depth the characteristics of visual response regulation when different SART targets are used during vection while controlling for the confounding factors. As discussed above, it is possible that regulation on visual

Table 2. Correlation coefficients, regression models for visual response regulation indicators and MSSQ scores.

Visual response regulation indicators			MSSQ scale score		
Experiment	Location	Target	MSSQ_C	MSSQ_A	MSSQ_T
Exp.1a	DRT_C	Static	−0.628* ($p = 0.011$)	–	−0.505* ($p = 0.039$)
	DRT_P		–	−0.573* ($p = 0.020$)	–
	TRT		–	−0.595* ($p = 0.012$)	−0.479* ($p = 0.042$)
Exp.1b	DRT_C	S0	−0.688** ($p = 0.002$)	–	−0.543* ($p = 0.018$)
		S16	−0.468* ($p = 0.039$)	–	−0.431^ ($p = 0.055$)
		S32	−0.527* ($p = 0.022$)	–	−0.353^ ($p = 0.098$)
	DRT_P	S0	−0.534* ($p = 0.025$)	–	−0.423^ ($p = 0.066$)
		S16	–	–	–
		S32	−0.413^ ($p = 0.068$)	–	–
	TRT	S0	−0.468* ($p = 0.039$)	–	−0.393^ ($p = 0.074$)
		S16	–	–	–
		S32	−0.476* ($p = 0.037$)	–	−0.303 ($p = 0.136$)

Regression model summary

Models	Predictors	*Beta*	*R*	R^2	*F*
1	SDRT_C	−0.307 ($p = 0.105$)	0.307	0.094	2.813 ($p = 0.105$)
2	STRT	−0.434* ($p = 0.019$)	0.434	0.188	6.249* ($p = 0.019$)
3	STRT	−0.575** ($p = 0.001$)	0.630	0.396	8.535**
	SDRT_C	−0.478** ($p = 0.006$)			($p = 0.001$)
	SDRT_P	Excluded			
4	SDRT_P	−0.455* ($p = 0.013$)	0.455	0.207	7.034*
	SDRT_C	Excluded			($p = 0.013$)

Notes:S0, S16, and S32 represent the speeds of 0, 16, and 32°/s, respectively. DRT correlation coefficients had controlled for individual overall RT; only marginal/significant results are included. SDRT_C, SDRT_P, and STRT represent standardised DRT_C, DRT_P and TRT, respectively, pooled from Exp. 1a and Exp. 1b. Model 1, 2 and 3 predict the MSSQ_T score; Model 4 (including SDRT_C & SDRT_P) specifically predicts MSSQ_C to address clinical concerns.
**$p < 0.01$; *$p < 0.05$; ^$p < 0.1$

response is achieved by reallocating one's attention from the CVF to the task of processing self-motion cues in the PVF. Therefore, the benefits of visual response regulation in the PVF are expected to be more evident with targets moving at similar speeds to the self-motion cues (H3a), while the impairment of visual response in the CVF should affect tasks equally regardless of the moving speeds of targets (H3b). Also, as this mechanism is supposed to facilitate sensory conflict reduction, individuals with stronger effect magnitude are expected to be less susceptible to VIMS (same as H2 in Exp. 1a).

Methods

Participants

A different group of 15 participants (9 male; Age: 20–27 years old, mean 24.6, SD 2.06) who met all of the requirements for Exp. 1a were recruited (see Appendix 1 for VIMS susceptibility distribution).

Apparatus and stimuli

Targets moving at different speeds were used in SART. Targets would appear for 500 ms and rotate around the screen centre at one of five rotating speeds (0, 16, 32, 64, −32°/s; 0 = static, positive value = anticlockwise). Moreover, to better control the background of targets and reduce the interference of rotating dot pattern, a black area (occupying 0~12.5° of FOV) was adopted to separate targets from peripheral vection-provoking stimuli. All targets only appeared within the black area and a white cross was used for fixation (Figure 1b). The same apparatus and procedures as those in Exp. 1a were applied to present stimuli and to restrict eye, head, and body movement and other environmental influences.

Procedures

The same SART paradigm from Exp. 1a was adopted. Sixty repetitions were conducted for each stimulus condition (CRS or IRS), each target location (CVF: 0~1.4° or

PVF: 6.3~9.4° of FOV; see Figure 1b) and each of the five target speeds. This gave 1200 trials (60 × 2 × 2 × 5). The trials were conducted in eight blocks (each containing 150 trials, length: 3~4 min). Repeated trials for each stimulus condition spanned more than four blocks and the combinations of target location and speed were randomised within each block. The order of blocks was randomised for each subject. The SART trial started 3 s after the vection-provoking stimulation to allow time for vection onset. To ensure performance was not affected by VIMS symptoms, participants took enough rest (3~5 min) between blocks. To reduce task difficulty for the sake of developing simple visual response regulation measures, subjects only needed to complete SART with their right hand and verbally report the duration of vection they experienced, based on an 11-point scale (0 = experienced no vection; 10 = experienced vection the whole time) after each block, as well as reporting the vection intensity. Reported vection intensity and duration were significantly stronger and longer under CRS than IRS (See Table 1).

Dependent measures

The RT and accuracy data obtained from all trials were averaged for the two types of stimulus conditions (CRS and IRS). Individual VIMS susceptibility is also measured using MSSQ-Short (Golding 1998) with two sub-scales (adult and child).

Results

An RMANOVA was conducted for each of RT and accuracy, with vection stimulus (CRS or IRS), location (CVF or PVF) and speed (0, 16, 32, 64, or −32°/s) as within-subject factors and individual MSSQ-Short scores (MSSQ_C and MSSQ_A) added as two covariates in the model. For RT, the interaction of vection × location × speed × MSSQ_A was significant for the cubic term [$F(1,12) = 5.489$, $p = 0.037$] and the interaction of vection × location × speed × MSSQ_C was marginally significant for the linear term [$F(1,12) = 3.538$, $p = 0.084$]. Due to the complicated interaction introduced by target speed, vection × location ($p = 0.090$) and vection × location × MSSQ_C ($p = 0.098$) were only marginally significant. As in Exp. 1a, subjects generally reacted more quickly in the CVF than PVF ($p = 0.001$). No significant accuracy differences were found, which ensures that no effect was due to a speed-accuracy trade off.

Effects in the PVF

Effects in the PVF diverged for different target speeds. The quadratic term of speed × MSSQ_C [$F(1,12) = 5.435$, $p = 0.038$] was significant and speed × MSSQ_A [$F(1,12) = 4.139$, $p = 0.065$] was marginally significant, while the cubic term of vection × speed × MSSQ_A was significant [$F(1,12) = 5.891$, $p = 0.032$]. Specifically, strong vection demonstrated significant modulation on RT for targets moving at different speeds. The simple main effect of speed was significant under CRS [$F(4,56) = 3.303$, $p = 0.017$, see Figure 2c] with the shortest RT for speed 32°/s and the longest RT for speed −32°/s, while no difference was found under IRS. Figure 2c better illustrates the effect of vection: participants reacted more quickly when targets were moving at similar speeds to the self-motion cues (especially for speed 32°/s, which was the same speed and direction with vection-inducing stimuli that providing self-motion cues), while more slowly when targets were moving at other speeds (especially for −32°/s, which was in the opposite direction to self-motion cues). In summary, specific improvement in SART performance was found in the PVF under strong vection condition (CRS), which was mainly focus on targets that were similar to self-motion cues (supported H1a).

Effects in the CVF

Similar to Exp. 1a, the vection × MSSQ_C term is significant [$F(1,11) = 5.634$, $p = 0.035$]. Likewise, vection simple main effect is marginal [$F(1,12) = 4.006$, $p = 0.068$], showing a longer RT in vection trials than control trials. Admittedly, the pure effect of vection was anticipated to be attenuated compared with that in Exp. 1a (simplified tasks might have made it impossible to exclude mixed vection trials under CRS/IRS). To further show that the delayed RT (DRT) in the CVF was associated with vection perception, we calculated the Pearson correlation between the vection duration (VD) difference (VD_{CRS}–VD_{IRS}) and DRT (RT_{CRS}–RT_{IRS}) of subjects. Results showed that subjects experienced vection for a longer period of time demonstrating larger performance impairments. The correlations were significant for all speeds (speed 0: $r = 0.689$, $p = 0.002$; speed 16: $r = 0.684$, $p = 0.002$; speed 32: $r = 0.700$, $p = 0.002$; speed 64: $r = 0.548$, $p = 0.017$; speed −32: $r = 0.502$, $p = 0.028$). Moreover, the simple interaction effect of vection × speed and the simple main effect of speed were not significant. In summary, general SART performance in the CVF was impaired under strong vection-inducing stimulation, regardless of target speed (supported H1b).

Interaction effects with speeds similar to those in Exp. 1a

To validate the findings in Exp. 1a, we further analysed that the data with speeds similar to Exp.1a (also similar to self-motion cues as explained above: 0, 16, and 32°/s) were included in the model. Both vection × location [$F(1,12) = 5.173$, $p = 0.042$] and vection × location × MSSQ_C [$F(1,12) = 7.256$, $p = 0.020$] were significant with no speed interaction, showing the exactly same pattern as in Exp.1a.

Correlation of effect magnitudes and MSSQ scores

As in Exp. 1a, to quantify the visual response regulation effects during vection, the delayed RT in the CVF (DRT_C), decrease in RT in the PVF (DRT_P) and total RT effects (TRT) were calculated for three speeds (0, 16, and 32°/s) that showed the same pattern as in Exp. 1a. To examine the relation between effect magnitudes and MSSQ scores, negative Pearson correlations between MSSQ-Short scores (MSSQ_T, MSSQ_C, and MSSQ_A) and the magnitude of effects (DRT_C, DRT_P, and TRT) were tested (see Table 2 for coefficients and *p*-values; see Figure 2b for scatter plots).

Furthermore, to evaluate the predictive power of effect magnitudes for MSSQ scores, we standardised and pooled the effects of static targets from all 29 subjects (including those in Exp. 1a and Exp. 1b). Three linear regression models (Model 1: central effects; Model 2: total effects; Model 3: central and total effects) for MSSQ_T and one model for MSSQ_C were tested using the stepwise method, where independent factors that contributed insignificantly were excluded (Table 2). Model 3 demonstrated the highest predictive power [R^2=0.396; $F = 8.535$, $p = 0.001$].

In summary, visual response regulation effects were negatively correlated with MSSQ scores, where VIMS-resistant subjects showed stronger effects than their susceptible counterparts (supporting H2). Moreover, the magnitude of measured effects can significantly predict individual MSSQ scores.

Vection and nausea report

Reported vection intensity and duration were significantly stronger and longer in CRS than IRS (See Table 1). No participants reported nausea, vomiting or other severe discomfort.

Discussion

Firstly, results of Exp. 1b confirmed the vection × location interaction findings from Exp. 1a with 15 different subjects and with tighter control of the background visual complexity. Furthermore, results support H3a and H3b, showing a general performance impairment in the CVF and specific improvement in the processing of self-motion cues in the PVF during vection. Note that this specific improvement also ensured that PVF effects were not due to the PVF targets blending in with the rotating dot pattern, or opposite results would have been obtained. As discussed in the section on Exp. 1a above, diverging SART performance suggests the reallocation of attention from the CVF to the PVF during vection. Increasing attention assignment can increase neurone reliability of the current visual input (Martínez-Trujillo and Treue 2002; Mitchell, Sundberg, and Reynolds 2007). According to previous studies, increased visual reliability would facilitate the weight shifting from vestibular to visual modality (Gu, Angelaki, and Deangelis 2008; Fetsch et al. 2012), which may yield less sensory conflict between the inner model and the visual input (Reason 1978; Brandt et al. 2002) under ambiguous vection-inducing conditions. This is also consistent with former studies reporting that VIMS is worse when vection is changing (less reliable) rather than stable (more reliable) (Bonato, Bubka, and Story 2005; Bonato et al. 2008). In summary, individuals who are able to reallocate their attention may be more resistant to VIMS, while those who fail to do so may be more vulnerable to optokinetic stimulation. This may explain the correlations we identified between visual response effects and MSSQ scores.

In addition, Exp. 1b also validated the negative correlation between individual VIMS susceptibility and magnitude of visual response regulation effects (H2). Although the simplified procedure mixed vection and no-vection trials which reduced the absolute effect size that could be measured, it still revealed significant correlation between effect magnitudes and MSSQ_C scores. Note that the use of static targets generally produced higher correlation coefficients, suggesting that this SART paradigm can be a promising candidate for VIMS susceptibility measurement. We explored the potential of static targets by pooling the results from Exp. 1a and Exp. 1b and obtained acceptable predictive power for MSSQ scores.

Experiment 2

As the previous two experiments suggested that reallocating one's attention from the CVF to the PVF can lead to more stable vection perception and prevent VIMS, we went on to explore whether attention allocation and vection perception could be guided using a revised SART. We hypothesise that if participants were only allowed to react to PVF targets while ignoring CVF targets, they would experience stronger and more stable vection than if they were only allowed to do opposite reactions (response to CVF targets while ignoring PVF targets) (H4). Moreover, the enhancement of vection would be stronger if the PVF targets also moved at the same speed as the self-motion cues (H5).

Methods

Participants

Thirteen of the 29 subjects who participated in Exp. 1a or Exp. 1b were invited to join Exp. 2 (7 male; Age: 19–27 years old).

Apparatus, stimuli and procedures

The same set of apparatus as that used in Exp. 1a and Exp. b was adopted. The same coherent rotating stimuli (CRS)

used in Exp. 1a were presented. Two modified SARTs were used to facilitate and control visual attention allocation in accordance to conditions. Such manipulation is a common paradigm for visual attention studies (e.g. Eggemeir and Wilson 1991; Morgan, Hansen, and Hillyard 1996; Müller et al. 1998). For the central-focused (CF) condition, subjects were instructed to press the response button as soon as targets appeared in the CVF, while ignoring targets appearing in the PVF. For the peripheral-focused (PF) condition, subjects were instructed to attend to the peripheral targets and ignore the central targets. The targets were all red discs (CVF/PVF ratio: 1/1). To test H5, two types of targets were designed: Self-motion cue targets which rotated at the same speed and in the same direction as coherent rotating stimuli; and non-cue targets (targets that do not provide self-motion cues) which rotated at the other speeds tested in Exp. 1b with equal probability. Target duration, trial interval and fixation were kept the same as in Exp. 1a. A total of 12 blocks (each containing 30 trials) were conducted, with three repetition blocks for each of the four experimental conditions in a randomized sequence (factorial combinations: 2 attention conditions × 2 target types × 3 repetitions = 12 blocks). All subjects received sufficient training before the actual experiment to ensure their response accuracy reached manipulation requirement (>95%). An eye tracker was used during the training session and throughout the actual experiment to ensure all subjects kept their eyes on the fixation circle for most of the time (>80%).

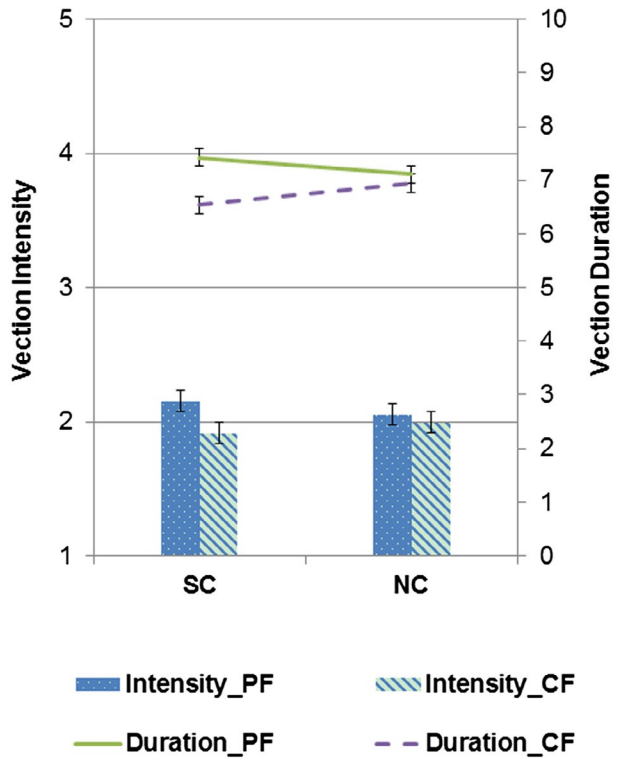

Figure 3. Effects of SART-guided attention reallocation on vection intensity and duration.
Notes: Task type: CF = central focused, PF = peripheral focused; Targets type: SC = self-motion cues, NC = non-cues; Vection intensity measured by self-report scale: 1 = no vection; 5 = saturated vection; Vection duration measures by self-rating scale: 0 = no experience of vection; 10 = experiencing vection all the time.

Dependent measures

Subjects were required to report their vection intensity and duration after each block based on the scales used in Exp. 1b. The ratings were averaged for each condition.

Results

All subjects accomplished responses for the two types of targets (attended targets/non-attended) with overall accuracy exceeding 95%. The main effect of attention allocation condition is significant for vection duration [$F(1,12) = 11.164$, $p = 0.006$] and marginally significant for vection intensity [$F(1,12) = 4.125$, $p = 0.065$], with subjects demonstrating stronger and a longer period of vection in the PF condition than the CF condition (supporting H4). Further simple effect analysis showed that the vection duration was only significantly different between PF and CF when self-motion cue targets were used [$F(1,12) = 7.341$, $p = 0.019$], but not when non-cue targets were used (supporting H2). Admittedly, the interaction between task type (PF or CF) and target type (self-motion cue or non-cue) is only a trend but not significant (Figure 3), possibly due to the large individual variations.

Discussion

This exploratory work demonstrated the promising effectiveness of SART training for attention reallocation under vection-inducing stimulation. Moreover, a more reliable and stable perception of vection was achieved during peripheral focused task, which is appealing for VR applications (e.g. video games). This suggests the possibility of redesigning visual tasks that are superimposed on a moving background to strengthen the vection perception. Moreover, this approach may also prevent VIMS, since more reliable and stable vection actually cause less VIMS (Reason 1978; Bonato, Bubka, and Story 2005; Bonato et al. 2008). Future studies exploring more direct evidence with a larger group sample are desirable.

Conclusions, limitations and future work

This study concludes that performance of visual tasks changes in the presence of vection. In particular, we find that the performance of visual tasks is impaired in the central visual field (CVF) and improved in the PVF. As discussed above, the current results and Brandt et al.'s (2002)

findings on the activation of visual cortices during vection suggest that people direct more attention to the PVF and less attention to the CVF when perceiving vection. Most importantly, the effect size of this attention reallocation is negatively correlated with VIMS susceptibility. In other words, individuals who are able to shift more of their attention to the PVF are also more resistant to VIMS. The shift in visual attention may imply an enhanced reliability of visual inputs and a relative reduction of vestibular weightings in the sensory integration, which, in a sensory conflicting situation, can reduce the conflicts (Brandt et al. 2002; Martínez-Trujillo and Treue 2002; Bremmer et al. 2016) and reduce VIMS (Reason 1978). It is worth mentioning that, the mechanism uncovered in this study focus on stabilising the visual motion input, which is different from traditional perspective that aiming to attenuate the motion input. As the self-motion perception and objective-motion (viewer stationary) perception are bi-stable states during vection-provoking stimulation (Kleinschmidt et al. 2002; Thilo, Kleinschmidt, and Gresty 2003), to reduce sensory conflict based on Reason's theory (1978), there should exist two optimisation directions: one traditional way is to reduce the peripheral visual motion/OKN and stabilise the stationary perception, which inevitably hurt the vection experience (Stern et al. 1990; Golding et al. 2012; Bonato, Bubka, and Thornton 2015); the other solution is to preserve the self-motion input and stabilise the self-motion perception (of constant speed). The phenomenon revealed in this study might be following the second direction, which can be quite promising, since it does not hurt the vection experience.

Moreover, in this study, sensory conflicts is referred as the general origin of all types of motion sickness (MS), while VIMS is considered as a specific type of MS introduced by virtual motion. VIMS susceptibility was accordingly measured with MSSQ, which is a general questionnaire for MS (Golding 1998). Since certain differences exist between VIMS and motion sickness caused by physical motion (Zhang et al. 2015), it is necessary to further explore whether the effects identified in this study may be more closely associated with other VIMS measures in the future. In addition, the CVF effect size along with the total effect of SART yielded surprisingly strong predictive power for individuals' MSSQ scores. Developing simple objective measures to predict individuals' susceptibility to VIMS without making people sick would be very useful (IWA3, 2005). Since SART can be conducted with few requirements on participants and results can be obtained quickly and easily, it is a promising candidate for measuring VIMS susceptibility and deserves to be further developed and validated.

Last but not least, results showed that attention reallocation can be trained, which agreed with previous findings (Szalma et al. 2018). Moreover, our results showed that this attention reallocation can lead to a more reliable and stable perception of vection under exactly the same visual stimuli. Since a more stable perception of vection may cause less VIMS (Bonato, Bubka, and Story 2005; Bonato et al. 2008), it is possible to redesign practical visual tasks in a VR environment to reduce motion sickness while maintaining the vection experience in VR. Follow-up studies to validate and further explore the relationship between VIMS and cognitive attention reallocation are appealing. Perhaps one day we can actively reduce our susceptibility to VIMS simply by shifting our attention.

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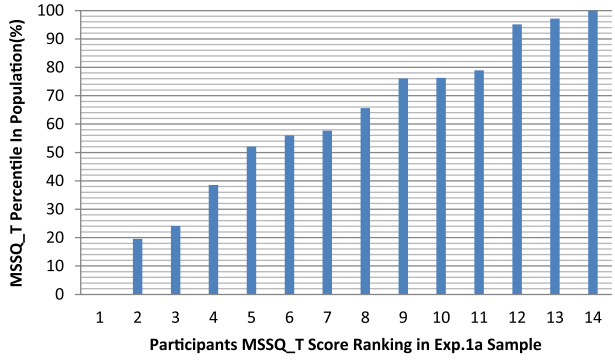
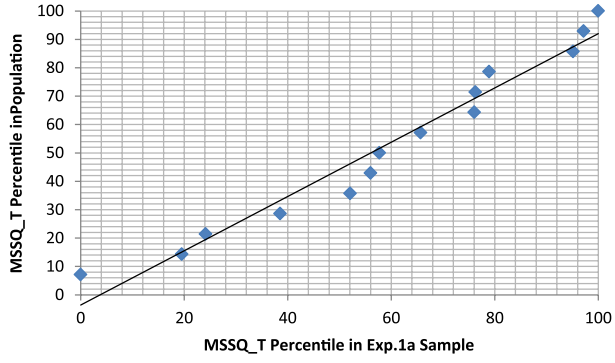
Appendix 1

Participants MSSQ score distribution in Exp.1a.





Participants MSSQ score distribution in Exp.1b.