Positive relations between vision and posture in the stationary gaze task performed upright

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Running head: vision-posture correlations in stationary gaze

Abstract

In upright stance, individuals sway in unpredictable ways. Their eyes also move in unpredictable ways in fixation tasks. The study's objective was to analyse visual functions, postural control and cognitive involvement in stationary gaze. Fourteen healthy young adults performed a stationary gaze task and a free-viewing task in addition (three trials per task, 45 sec per trial). As expected, the results showed many (n=32) significant positive Pearson correlation coefficients between eye and center of pressure/body (head, neck, lower back) movements in stationary gaze and *ns* in free-viewing. Only 3/32 significant correlations (9.4%) were significantly related to the cognitive involvement (measured with a subjective questionnaire). As discussed, these results indirectly strengthened the validity of the synergistic model of postural control.

Keywords: stationary gaze; quiet stance; eye-body related movements; correlations; cognitive involvement; young adults

1. Introduction

In the literature on postural control, many investigators have studied the movements of the body in one or several tasks and used the stationary gaze task to provide baseline data to better understand their results (e.g. Kapteyn et al., 1983; Raymakers, Samson & Verhaar, 2005). In this stationary gaze task, participants generally look at a stationary target in front of them located at eye height. This task seems very easy, basic. However, it may not be so easy to maintain the eyes on a stationary target because individuals sway continuously in an irregular, nonlinear, nonstationary way (Bonnet et al., 2010; Collins & DeLuca, 1995; Riley & Turvey, 2002). Moreover, microsaccades can alter the stationary gaze (Otero-Millan et al., 2008; Thaler Schütz, Goodale & Gegenfurtner, 2013) as they are erratic (Engbert & Kliegl, 2004). Consequently, in a stationary gaze task performed upright, the images on the retinas are always changing (Aytekin & Rucci, 2012).

In the literature reports, many investigators have studied the interaction between visual functions and postural control in upright stance (e.g. Giveans et al., 2011; Legrand et al., 2013; Rougier & Garin, 2007; Schulmann, Godfrey & Fisher, 1987; Stoffregen, Bardy, Bonnet, Hove & Oullier, 2007; Thomas et al., 2016). In these studies, the stationary gaze task was systematically used as a basic or control task but never as the task of interest. These studies generally analysed how pursuit visual tasks (Schulmann et al., 1987; Thomas, Bampouras, Donova & Dewhurst, 2016) and/or saccadic left-right tasks (Giveans et al., 2011; Rougier & Garin, 2007) and/or precise detections (Legrand et al., 2013; Stoffregen et al., 2007) could influence postural control. In other studies, investigators studied how a moving visual environment (Laurens et al., 2010) and/or a sway-referenced platform (Alahmari et al., 2014), or the proximity of the visual environment (Bonnet et al., 2010) could influence postural control.

In the present study, our first objective was to analyse the interaction between postural control and/or visual functions in the stationary gaze task. What could be expected in the relation between eye movement on one hand and COP and/or body movements – now called COP/body movements – on the other hand in the stationary gaze task was not obvious. Firstly, negative correlations could be expected between eye and COP/body movement if the eyes moved exactly in the opposite direction and in phase with COP/body movements. For example, if the body was swaying on the left, the eyes should move on the right with the same amplitude and in phase with body movements to keep staying on the target. Secondly, only positive correlations between eye and COP/body movements could be expected if the correlations between eye and COP/body movements were only spatial, i.e. not correlated along time. For example, the body could sway on the left and the eyes could move on the right but with some delays or some imprecisions. Thirdly, there could be no significant correlation between eye and COP/body movements as the eyes move very quickly with no inertia while the body is heavy. In fact, we expected the second hypothesis to be the best one because there should exist significant relations between eye and COP/body movements to explain why the participants easily succeed in stationary gaze although unpredictable microsaccades and differences in inertia could impeach perfect subtle relations.

We also studied the relations between eye and COP/body movements to test – indirectly yet – the synergistic model of postural control. To clarify this second objective, we first need to define the synergistic model (Bonnet & Baudry, 2016) and second explain what the results in the stationary-gaze task could inform us. In fact, the synergistic model was created to explain/predict relations between eye and COP/body movements in precise visual tasks, i.e. in tasks requiring precise gaze shifts on aspects of the visual environment. It was not intended to analyse stationary gaze. In precise visual tasks, our model expects that functional relations should exist between eye and COP/body movements. This is the first most important hypothesis. Here, the term “functional relations” refer to complementarity between eye and

COP/body movements to succeed in precise gaze shifts. For example, if an individual wants to perform a precise saccade of 10° on the left and if he/she sways a corresponding angle of 0.1° on the left at the same moment, he/she would need to perform a gaze shift of 9.9° and not 10° to reach the target straight with no corrective saccade. The model was called “synergistic” because eye and body movements are expected to be coordinated, complementary to succeed in precise visual tasks. However, it should be acknowledged that there is no muscle or reduction of degrees of liberty in this synergistic model of postural control (Bonnet & Baudry, 2016).

The synergistic model was validated once in Bonnet, Szaffarczyk and Baudry, (2017). In this study, we found functional relations between eye and body movements in a search task because healthy, young individuals exhibited only negative Pearson correlations between eye and body (i.e. head and neck) movements. These negative correlations were assumed as functional because the larger the gaze shifts, the lower the individual swayed. In the literature, it is well admitted that a decrease in postural sway is representative of functional, or adaptive, postural control while an increase in postural sway shows a weakened postural control (e.g., Bonnet & Baudry, 2016; Mitra, Knight & Munn, 2013). In the non-precise control free-viewing task (free-viewing exploration with no goal), we could not find any functional relations, i.e. any negative correlations, but only positive ones. These positive correlations were interpreted as non-functional because the larger and faster individuals explored their environment, the larger and faster they swayed, which should be counter-productive to perform precise gaze shifts. In Bonnet et al. (2017), we did not analyse relations between eye and COP/body movements in the stationary gaze task because these relations could not directly test the model. Indeed, there is no precise gaze shifts in this task.

In Bonnet et al. (2017), we also showed that the subjective cognitive involvement was significantly higher in searching than in free-viewing. Moreover, controlling for the influence of the cognitive involvement cancelled all significant negative correlations between eye and body movements in the precise search task. We concluded that the CNS may have increased its cognitive engagement to better control upright stance in order to functionally link eye and body movements in the precise task while it did not do so in the non-precise visual task (for more details, see Bonnet et al., 2017). One theoretical issue in this study is that individuals performed, on average, longer fixations in searching than in free-viewing. Long fixations may have had a confounding effect on the results, i.e. they may have induced the significant negative vision-posture correlations in searching. Hence, we needed to check whether a fixation task (with long stationary gazes) could actually lead to significant negative correlations between eye and COP/body movements. If so, the negative correlations found in the search task in Bonnet et al. (2017) would not result from a functional relation between eye and COP/body movements but would merely depend on longer fixations in the search task. Overall therefore, testing correlations between eye and COP/body movements in a stationary gaze task could indirectly invalidate the concept of functional relations between eye and COP/body movements proposed in Bonnet et al. (2017). The term “indirect” is used here because the synergistic model can only be tested directly with the results of a precise visual task.

The specific analyses of relations between eye and head movements could also be used to study the vestibulo-ocular reflex (VOR) in quiet stance; it was a third (secondary) objective of the present study. By definition, the VOR is useful to stabilize vision in moving the eyes and head in counter-balanced directions with a ratio close to 1 in terms of gain (McGarvie et al., 2015; Mossman, Mossman, Purdie & Schneider 2015) and almost with no delay (Huterer & Cullen, 2002; Sparks, 2002). So far, it does not seem that eye and head movements were measured simultaneously in healthy, young adults to test the functionality of the VOR. Indeed, we could only identify studies testing the VOR in patients (mainly with vestibular problems), older adults and healthy children. In these studies, the participants performed a quiet stance task and a test in a rotational chair. Then, the amplitude of postural sway measured in quiet stance was correlated with the gain of the VOR measured in the seated condition (Allum & Honegger, 2013, 2016; Baloh, Ying & Jacobson, 2003; Charpiot, Tringali, Ionescu, Vital-Durand & Ferber-Viart, 2010). In the present study, we tested if specific correlations between eye and head movements could be positive or negative in upright stance and we tested the reflex-like nature of these interactions.

In brief, the study's purpose was to explore correlations between eye and COP/body movements specifically in the stationary gaze task performed upright. Fourteen healthy, young adults performed a main stationary gaze task. In this task, we rejected the possibility to find negative significant correlations between eye and COP/body movements and instead expected to find only significant positive ones. The participants also performed a free-viewing task in which they randomly looked at an image. This task was also used to indirectly test the synergistic model. In this free-viewing task, we expected to find only significant positive correlations between eye and COP/body movements, as in Bonnet et al. (2017). A lower quantity of significant positive correlations and lower correlation coefficients were expected in the free-viewing task than in the stationary-gaze task. In both tasks, we did not expect that changes in cognitive involvement would be required to get the significant correlations between eye and COP/body movements. Indeed, stationary gaze may be a reflex-like activity that does not need to engage additional cognitive involvement. The free-viewing should consist of random-looking gaze shifts that also do not engage any additional cognitive involvement.

2. Methods

2.1. Participants

Fourteen healthy young adults (7 females, 7 males) were included in the study. The mean age, bodyweight and height were 20.43 ± 1.70 years, 68.07 ± 11.25 kg and 1.71 ± 0.1 m, respectively. The study was performed in accordance with the tenets of the Declaration of Helsinki. The participants gave their written, informed consent to participation.

2.2. Apparatus

A dual-top force platform (AMTI, Watertown, MA, USA) was used to record COP displacement with a sampling frequency of 120 Hz. Three markers of the Polhemus system (LIBERTY 240/8-8 System, Polhemus, Colchester, VT, USA) were placed behind the participants at the head, neck and lower back levels (cf. Figure 1A). They recorded angular (yaw, pitch, roll) and linear (anteroposterior (AP), mediolateral (ML), vertical) time-series with a sampling frequency of 240 Hz. The head and lower back markers were placed on a helmet and on a chest belt worn by the participants (Figure 1A). The neck marker was fixed on the neck at the seventh cervical vertebra (cf. Figure 1A) with a scotch tape. A SMI eye-tracker (SensoMotoric Instruments, Teltow, Germany) was set on the helmet and recorded the position of the eyes with a sampling frequency of 50 Hz. All these devices were synchronized with the images projected 3.40 m in front of the participants.

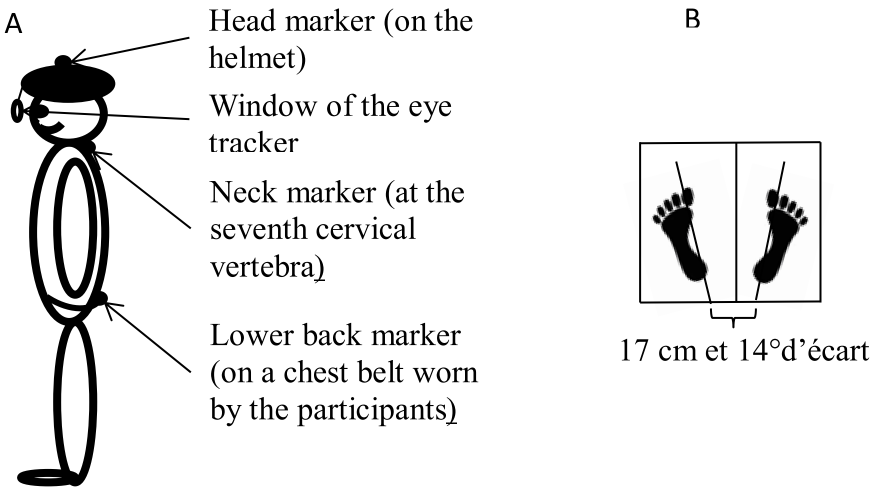

Figure 1. Two images projected in front of the participants. Only the part within the circle was apparent to the participants (within a circle subtending a visual angle of 22°).

A French version (Cegarra & Morgado, 2009) of the multidimensional National Aeronautics and Space Administration Task Load Index (NASA-TLX) questionnaire (Hart & Staveland, 1988) was used to record the cognitive workload after each task. As (Bonnet et al., 2016), this questionnaire was chosen because it is a well validated questionnaire sensitive to fine variations between tasks (Cegarra & Morgado, 2009). This questionnaire already showed significant differences in subjective cognitive engagement between the free-viewing and fixation tasks (Bonnet et al., 2017; Bonnet & Szaffarczcyk, 2017).

2.3. Conditions

The participants performed three trials in each of the stationary gaze and free-viewing tasks. In each trial, images of real life in a town (streets, buildings) were projected at eye-height onto a circle of 22° (Figure 2A and B). The three images were the same in both tasks. In the stationary gaze task, the participants had to fixate on a black cross centred in the circle for the duration of the trial (45 sec). In the free-viewing task, the black cross was also present for 3 seconds and the participants had to look at it. Once the black cross disappeared, the participants could freely look at the image randomly with no goal. In both tasks, they had to avoid any voluntary movement (e.g. hand movements). They were told to relax and hold their arms by the side of the body. The free-viewing task did not serve as a control for the stationary gaze task but served to bring complementary data, as discussed below.

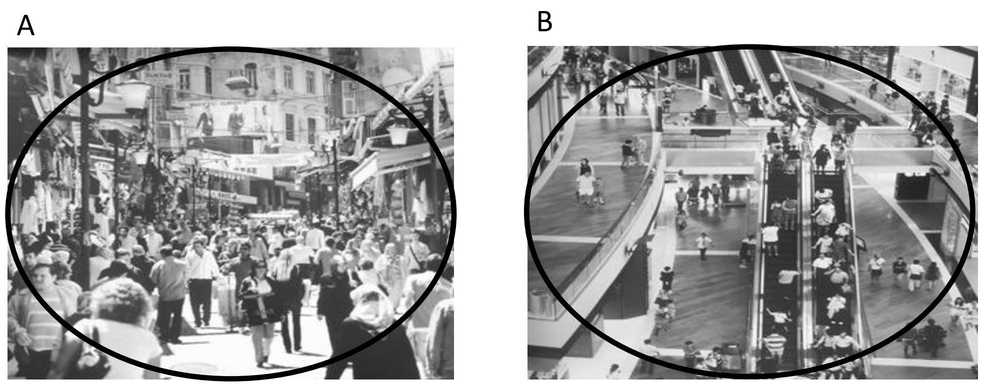

Figure 2. A) Image showing the position of the Polhemus markers and of the eye tracker; B) Image showing the position of the feet on the dual force platform.

2.4. Procedure

During each trial, the participants were barefoot with their feet positioned along two normative lines (17 cm, 14°; McIlroy & Maki, 1997, Figure 1B). The two conditions (stationary gaze, free-viewing) were run one after another in a counter-balanced way. The participants filled the NASA-TLX questionnaire after each task in a seated position (for a rest period of about 5 min). Between each trial, the participants could relax 20-30 sec. This duration was required to allow the investigator to record the data and to prepare the next trial.

2.5. Variables

The standard deviation (SD), range (R) and mean velocity (V) of COP, markers and eye displacements were used to analyse body and eye movements on the AP and ML axes. The path length and ellipse area were also used to provide a general trend of eye and body movements. The ellipse area variable calculated the characteristics of an ellipse which captured 85 % of eye movements (Latash et al. 2002). The SD, R, ellipse variables concerned the amplitude of eye and COP/body movements while V and path length were more related to the velocity of eye and COP/body movements. We computed these two kinds of movement characteristic to provide a global scheme of relation between of eye and COP/body movements. We expected consistent results with all these variables. The NASA-TLX global score was determined for each task as recommended (Cegara & Morgado, 2009; Hart & Staveland, 1988).

2.6. Analyses

Four analyses were performed: i) Pearson correlations between eye and COP/body movements in the stationary gaze and free-viewing tasks separately; ii) partial correlations between eye and COP/body movements in both tasks separately controlling for – eliminating for – the NASA-TLX's influence on these correlations. These partial correlations were only performed on the significant Pearson correlations found in the previous analyses; iii) cross-correlation analyses between eye and COP/body time-series in both tasks and both axes separately (ML body movements cross-correlated to left-right eye movements; AP COP/body movements cross-correlated to the corresponding up-down eyes movements); iv) Pearson correlations between all COP/body movement variables and all variables of the visual functions to show potential redundant correlations. These Pearson correlations wereonly performed for all the significant correlations between eye and COP/body time-series found earlier in both tasks and axes. Pearson correlations were assumed to look at gross relations between variables (only on one value) while cross-correlations were assumed to look at subtle relations between variables. Indeed, by definition, cross-correlation is a measure of similarity of two time-series as a function of the displacement of one relative to the other (Wikipedia).Pearson correlations searched to know if one average quantity of COP/body movement could be related to a corresponding average quantity of eye movement. Cross-correlations firstly determined the strength of coupling between eye and COP/body movements for each participant in each task. A first Matlab script was used to resample the COP, head, neck, lower back time-series at 50 Hz. A second Matlab script was used to obtain the cross-correlation coefficients between eye and COP/body movements for each trial. Secondly, one-way repeated measure ANOVAs (factor: tasks) were performed to compare the coefficients in both tasks. Eight ANOVAs were performed between left/right eye movement and mediolateral COP, lower back, neck, head movement and between up/down eye movement and anteroposterior COP, lower back, neck, head movement. All analyses were exploratory and performed with an adjusted *p*-value ($p<0.01$). They were performed with Statistica 10 Software (Statsoft Inc., Tulsa, OK, USA).

Pre-analyses were performed and only showed an outlier in the data for the ellipse of trunk movement. Hence, this set of data was not analyzed in the correlation analyses below.

3. Results

3.1. Significant Pearson correlations between eye and COP/body movements

In stationary gaze, our exploration of significant Pearson correlations between eye and COP/body movements showed thirty-two significant positive coefficients (Table 1). Four of these significant correlations are showed in Figure 3A, b, C and D. In free-viewing, no Pearson correlation was significant, *ns* (Table 1).

Insert Table 1 about here

Figure 3.

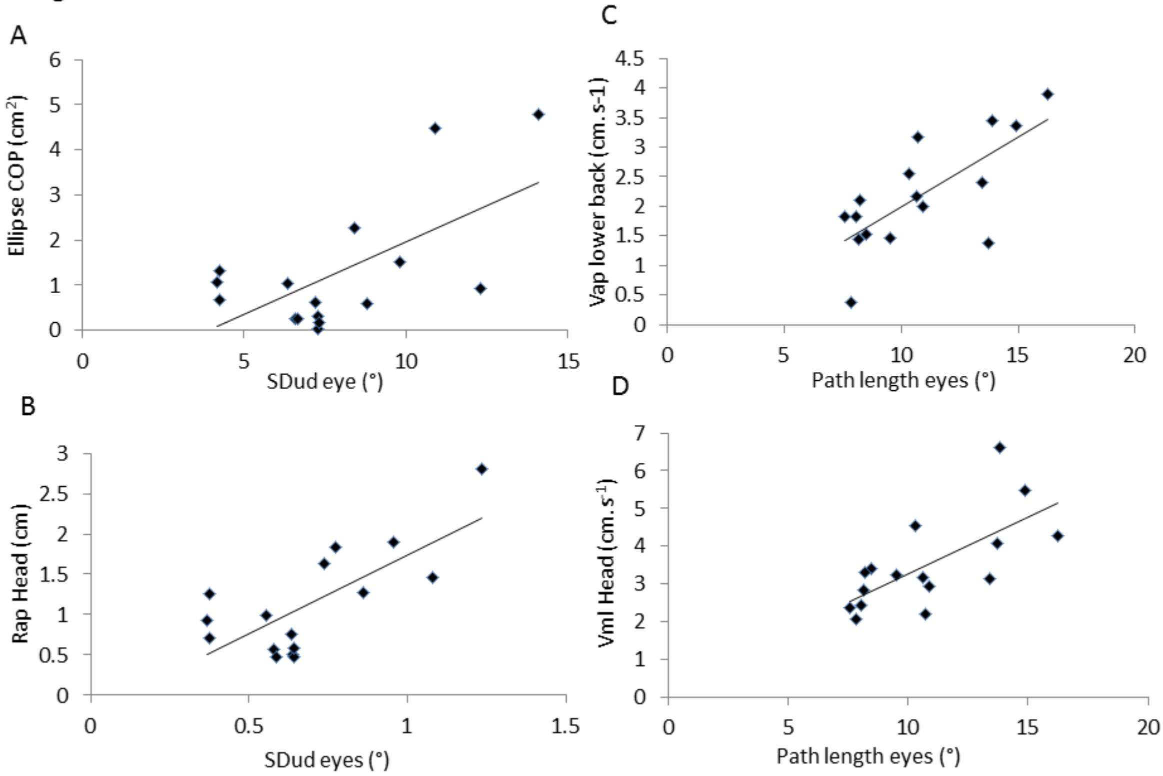

Figure 3. A) significant Pearson correlation (p<0.01) between the standard deviation of eye movement in the up-down direction (SDud eye; in degrees, °) and the ellipse area of the COP movement (Ellipse COP; in cm^2); B) Significant Pearson correlation between SDud eye (°) and the range of head movement on the anteroposterior axis (Rap Head in cm); C) Significant Pearson correlation between the path length of eye movement (path length eyes, °) and the velocity of the lower back movement on the anteroposterior axis (Vap Lower back, $cm.s^{-1}$); D) Significant Pearson correlation between path length eyes (°) and the velocity of the head movement on the mediolateral axis (Vml Head, $cm.s^{-1}$). p<0.01.

3.2. Significant partial correlations between eye and COP/body movements, controlling for the NASA-TLX global score's influence

In stationary gaze, three of the thirty-two significant correlation coefficients with COP, lower back, neck and head movements were not significant anymore when controlling for the NASA-TLX global score's influence. After controlling for this NASA score, i) the correlation between the standard deviation of up-down eye movement and the ellipse area of COP movement changed from $r(16) = 0.632$, $p < 0.01$ (cf. bold result in Table 1) to $r(16) = 0.631$ $p = 0.012$; ii) the correlation between the path length of eye movement and the mean velocity of neck movement on the ML axis changed from $r(16) = 0.63$, $p < 0.01$ (cf. bold result in Table 1) to $r(16) = 0.62$, $p = 0.013$; ii) the correlation between the path length of eye movement and the mean velocity of lower back movement on the ML axis changed from $r(16) = 0.63$, $p < 0.01$ (cf. bold result in Table 1) to $r(16) = 0.62$, $p = 0.015$.

3.3. Significant difference in cross-correlations between both tasks

The eight cross-correlations (COP, lower back, neck head on the AP and ML axes) were not significantly different in stationary gaze and free-viewing ($F_s(1,15) < 5.32$, $p>0.01$, *ns*).

3.4. Non-redundant correlations between eye and COP/body movements

In chapter 3.1, we showed 32 significant correlations between eye and COP/body movements (Table 1). However, some or many of these correlations could be redundant. For this reason, we checked significant Pearson correlations between all postural variables on one hand and all variables of the visual function on the other hand. These new analyses showed that most of the variables were correlated to one another and we could only identify 4 independent correlations between eye and COP/body movements. These 4 correlations are showed in Figure 3A, B, C and D. We should note that when many postural and/or visual variables were correlated to the same visual and/or postural variable, we selected the significant correlation with the highest *r*. One should notice that all significant correlation coefficients were close to one another. Hence, the choice of the 4 specific correlations showed in Figure 3A, B, C and D merely depends on this criterion, it is arbitrary and does not exclude the fact that the relevant correlation could be different – i.e. with other parts of the body movement – than the ones shown in Table 1.

4. Discussion

In the present study, we investigated correlations between eye and COP/body movements in stationary gaze and free-viewing tasks performed upright. As expected, the results showed stronger significant correlations in stationary gaze than in free-viewing; they actually showed significant positive correlations only in stationary gaze (32 ones vs. 0). Many of these correlations were redundant and only four of them were independent of each other. The cognitive involvement was not significantly related to any of the 4 independent significant correlations and only significantly related to 3 of the 32 significant correlations found (9.4 %), thus showing that the subjective cognitive involvement may only minimally influence them in stationary gaze. Below, we discuss significant correlations between eye and head movements in stationary gaze to explain how these analyses and results could serve to test the functionality of the VOR in upright stance.

4.1. Interest in visual functions and postural control in the stationary gaze task

The visual task of looking at a stationary target upright is an active process (Aytekin & Rucci, 2012). Indeed, postural sway upright is continuous, irregular, nonlinear, nonstationary (Bonnet et al., 2010; Collins & DeLuca, 1995; Riley & Turvey, 2002) and the eyes are also affected by small unpredictable eye movements (Engbert & Kliegl, 2004; Otero-Millan et al., 2008; Thaler et al., 2013). However, even in these conditions, individuals perceive a stable visual environment. This visual stability is useful to well recognize forms, colours, textures, to enable the acquisition of visual information (Colagiorgio, Colnaghi, Versino & Ramat 2013) and to avoid visual blurring (Herdman, Schubert, Das & Tusa, 2003).

In the present study, our main objective was to analyse linear correlations between eye and COP/body movements in the stationary gaze task. We were not aware of any similar literature reports. We found only positive correlations between eye and COP/body movements in this stationary gaze task (with COP, head, neck and lower back, Table 1, Figure 3A, B, C and 3D) but no cross-correlation between eye and COP/body movements. These results thus showed that eye and COP/body movements are not related in a strong manner in a stationary-gaze task performed in quiet stance. Instead, they were only related in a gross manner (only with mean characteristics of time-series), as originally expected. However, important is to note that eye and COP/body movements were indeed significantly related to one another in many ways (Table 1).

The results also showed no significant correlation in the free-viewing task (Table 1), hence validating our hypothesis that stronger link between eye and COP/body time-series could be found in stationary gaze than in free-viewing. The strength of the relations in stationary gaze was also higher than the relations in free-viewing in our previous study (4 positive correlations; Bonnet et al., 2017)[1]. Both differences in the respective numbers of significant correlations are important because we used the same variables and analyses in both studies. Therefore, the stationary gaze task firmly required significant relations between the eyes and body movements, as suggested by Aytekin and Rucci (2012). Cautiously, the number of significant correlations should be considered cautiously because many of the correlations were redundant, i.e. significantly related to each other. Only four correlations between eye and COP/body movements were independent of each other (Figure 3A, B, C & D). This redundancy is informative because it showed that similar body movements were performed at different levels of the body, i.e. that the head, neck, lower back moved in-block with respect to eye movements.

4.2. Influence of the subjective cognitive involvement on the relations between eye and COP/body movements

In the present study, we did not expect to find any significant influence of the cognitive involvement on the correlations between eye and COP/body movements because both free-viewing and stationary gaze were easy, basic, tasks (Bonnet & Baudry, 2016). The results indeed validated our hypothesis because in the stationary gaze task only 9.4% (n=3/32) of the significant eye-body correlations were influenced by changes in the subjective cognitive involvement, just a little bit above chance (Table 1). Moreover, none of the 4 most important relations between eye and COP/body movements were significantly related to the cognitive involvement. Hence, the subjective cognitive involvement only marginally changed the correlations between eye and body movements in stationary gaze. We need to mention that the NASA-TLX questionnaire was useful and appropriately used to study the subjective cognitive involvement in the stationary gaze task. Indeed, in both Bonnet et al. (2017) and Bonnet and Szaffarczyk (2017), we showed that the NASA-TLX global score was significantly higher in

[1] In Bonnet et al. (2017) we did not check if the 4 significant correlations could be redundant or not.

the stationary gaze task than in the free-viewing task. The stationary gaze task is indeed psychologically constraining as it requires to keep the eyes continuously on a target without looking around.

4.3. Indirect validation of the cognitive nature of the synergistic model in both free-viewing and stationary gaze tasks

The synergistic model expects that there should exist functional relations, i.e. negative correlations, between eye and COP/body movements in precise visual tasks, not in any other visual task. In Bonnet et al. (2017) we indeed hypothesized and found only negative correlations between eye and COP/body movements in a precise task. We showed that the larger and faster the young participants moved their eyes precisely on the target and the lower and slowed they swayed (cf. Bonnet et al., 2017). If the present study had shown significant negative correlations between eye and COP/body movements in the stationary gaze task and/or in the free-viewing, these results would have caused an issue for the validity of the model. Indeed, these negative correlations in the stationary gaze task would have suggested that it is not the act of searching that required functional relations between eye and COP/body movements – as discussed in Bonnet et al., 2017 – but simply the act of staring at various targets. In the free-viewing task, if we had found negative correlations between eye and COP/body movements, it would have suggested that it is not the act of searching that required functional relations between eye and COP/body movements but simply the act of moving the eyes randomly on images. Our results with only positive correlations in stationary gaze (Table 1, Figure 3A and 3B) and *ns* in free-viewing thus indirectly reinforced the validity of the synergistic model in complement to Bonnet et al. (2017). Furthermore, the present results did not show any influence of the subjective cognitive engagement on the 4 non-redundant (Figure 3A, B, C, & D) or on most (91.6%) of the 32 significant correlations between eye and COP/body movements (Table 1) in the stationary gaze task. We recall that this link definitely existed for the negative correlations between eye and COP/body movements in the precise visual task in Bonnet et al. (2017, 100% of the times).

Carefully, the results of the correlations between eye and COP/body movements do not have the same meaning in stationary gaze vs. free-viewing and search tasks. On one hand, the positive Pearson relations in stationary gaze showed that larger and faster head movements were accompanied by counterbalanced larger and faster eye movements to succeed in keeping the eyes on the stationary target (Table 1). In contrast, the positive Pearson relations in free viewing found in our former study (Bonnet et al., 2017) most likely showed a destabilizing relation between eye and COP/body movements because larger and faster eye movements were accompanied by larger and faster COP/body movements to fully explore the image. This situation can be interpreted as destabilizing because gaze shifts cannot be precise when the body moves too much and too quickly. In this situation, larger eye movements should be accompanied by fewer precision.

4.4. Correlations between eye and head movements in stationary gaze

As stated in our Introduction, the VOR moves the eyes and head in counter-balanced directions with a gain almost equal to 1 (McGarvie et al., 2015; Mossman et al., 2015) and a very small phase delay of 5 ms (Huterer & Cullen, 2002; Sparks, 2002). The literature reports thus already showed that eye movements are strongly correlated to head movements. Our results showed ten significant correlations between eye and head movements (Table 1) thus validating this general phenomenon. Among these correlations, two were non-redundant significant correlations (Figure 3B and 3D). These findings complete the literature reports because they were described with correlation analyses and not with a ratio. Moreover, the test were not performed with participants seated (e.g. Allum & Honegger, 2013, 2016; Balow et al., 2003; Charpiot et al., 2010) but upright. All the correlation coefficients showed in Table 1 were not close to 1 (all $0.63<r<0.76$), as the usual ratio with the VOR gain because the paradigms were different. On one hand, the VOR gain should be high when the body is largely perturbed, for example when individuals are rotated passively on a rotational chair. On the other hand, the VOR gain should be lower when the body stands quietly upright as in our study. Accordingly, Aytekin and Rucci (2012) explained that the gain of oculomotor compensation was lower than 1 when the head was not restrained. The duration of the trials also matters to explain this contrast between studies. Both Aytekin and Rucci (2012) and Engbert & Kliegl (2004) explained that the performance of stationary gaze could not be perfect because of microsaccades. These microsaccades could have influenced our results because the participants looked at the target for a long time, i.e. 45 seconds, and not a few seconds as in the test with the rotational chair. In conclusion, it seems expected to obtain high VOR gain and high negative cross-correlations between eye and head/body movements in dynamic/perturbing situations but lower VOR gain and no negative eye and COP/body movements in quiet stance.

We studied the influence of the subjective cognitive involvement on the ten significant correlations between eye and head movements and found no effect at all. Hence, these results validated that our method may capture the reflex nature of these correlations (Table 1). In other words, our analyses and results may test the functionality of the VOR in upright stance.

4.5. Summary and perspectives

Taken as a whole, the present exploratory study showed that only significant positive relations between eye and COP/body movements could be found in stationary gaze. These results will serve to provide a basis for future studies. The present study also showed that these interactions could be reflex-like, as there was almost no influence of the cognitive involvement on these previous results. A limitation of the present study relates to the fact that we only used a subjective questionnaire to evaluate the cognitive involvement *after* each task. A best solution would have been to measure the cognitive involvement *during* each task – e.g. with measures of electroencephalography or near-infrared spectroscopy – or with the addition of another cognitive task. A future study should take care of this shortcoming and also look at age-related and disease-related impairments in both the efficiency to maintain the gaze stationary in a stationary gaze task. These investigations are important because postural control seems to decline more rapidly and intensely with age than the VOR gain (Hegeman, Shapkova, Honegger & Allum, 2007; McGarvie et al., 2015; Mossman et al., 2015) and because Parkinson disease-impairments in eye (Ekker et al., 2017) and motor (Falaki et al., 2016) relations have already been found.

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Table 1.

Significant Pearson's correlations between eye and head, neck, lower back and center of pressure (COP) movements in the anteroposterior (AP) and mediolateral (ML) directions and in the stationary-gaze and free-viewing tasks ($p<0.01$). For each of the 32 significant Pearson correlations, the first variable is systematically the visual variable and the second one is the postural variable. The two relationships in bold were not significant anymore when the influence of the cognitive involvement was controlled in partial correlations.

	In the stationary-gaze task
Correlations between eye and head displacements	In the up-down/AP directions: SD & Rhead (*r*(16)=0.73); SD & SDhead (*r*(16)=0.75); SD & ellipse area head (*r*(16)=0.69); Path length & Vhead (*r*(16)=0.69); Path length & path length head (*r*(16)=0.70); Ellipse area & Rhead (*r*(16)=0.72); Ellipse area & SDhead (*r*(16)=0.73); Ellipse area & ellipse area head (*r*(16)=0.70); In the left-right /ML directions: Path length & Vhead (*r*(16)=0.69); Ellipse area & Rhead (*r*(16)=0.66)
Correlations between eye and neck displacements	In the up-down/AP directions: SD & Rneck (*r*(16)=0.69); SD & SDneck (*r*(16)=0.74); SD & ellipse area neck (*r*(16)=0.68); Path length & Vneck (*r*(16)=0.69); Path length & path length neck (*r*(16)=0.68); Ellipse area & Rneck (*r*(16)=0.71); Ellipse area & SDneck (*r*(16)=0.74); Ellipse area & ellipse area neck (*r*(16)=0.70); In the left-right /ML directions: **Path length & Vneck (*r*(16)=0.63)**; Ellipse area & Rneck (*r*(16)=0.65)
Correlations between eye and lower back displacements	In the up-down/AP directions: SD & Rlower back (*r*(16)=0.68); SD & SDlower back (*r*(16)=0.72); SD & ellipse area lower back (*r*(16)=0.67); Path length & Vlower back (*r*(16)=0.72); Path length & path length lower back (*r*(16)=0.72); Ellipse area & Rlower back (*r*(16)=0.73); Ellipse area & SDlower back (*r*(16)=0.76); Ellipse area & ellipse area lower back (*r*(16)=0.71) In the left-right /ML directions: **Path length & Vlower back (*r*(16)=0.63)**
Correlations between eye and COP displacements	In the up-down/AP directions: SD & Ellipse area (*r*(16)=0.63) In the left-right /ML directions: Ellipse area & SD (*r*(16)=0.65); Ellipse area & ellipse area (*r*(16)=0.66)

Note. The above dependent variables of the eyes and COP/body displacements were the range (R), the standard deviation (SD), the mean velocity (V), the path length and ellipse area. The displacements of the eye in the up-down direction were systematically correlated with the displacements of the body on the AP axis and the displacements of the eyes in the left-right direction were systematically correlated with the displacements of the body on the ML axis. However, the variables with no direction (path length or ellipse area) were correlated with the variables in both directions (AP and ML or up-down and left-right). The direction of each variable is only cited at the beginning of each line in Table 1.