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# Relations between Eye Movement, Postural Sway and Cognitive Involvement in Unprecise and Precise Visual Tasks

**Cédrick T. Bonnet,[a,*] Tanguy Davin,[a] Jean-Yves Hoang[a] and Stéphane Baudry[b]**

[a]*SCALab, CNRS UMR 9193, University of Lille, France*

[b]*Laboratory of Applied Biology and Neurophysiology, Université Libre de Bruxelles, FNRS, Belgium*

**Abstract—We studied eye and body movements in 16 healthy young adults who performed visual tasks in upright stance. Our objective was to investigate whether these movements could be functionally related to each other when performing a precise visual task requiring large ecological gaze shifts. We also questioned the influence of an additional counting task on these relations. The participants performed searching (precise), free-viewing (unprecise) and gaze-fixation (basic) either alone or in counting silently backwards in sevens. For the search task, the participants had to visually locate as many targets as possible in the images. For the free-viewing task, they had to watch images randomly. Based on a recent model, we expected to find negative correlations between eye and center of pressure and/or body (lower back, neck, head) movements only in the search tasks. The double search–counting task was expected to increase the number of negative correlations. The results confirmed both hypotheses in both search tasks, with relations mainly between eye and head movements (89% of the time). The subjective cognitive involvement (significantly higher in searching than in free-viewing and gaze-fixation) was significantly related to all (100%) and to half (50%) of these previous correlations in search–counting and searching, respectively. Complementarily, the participants rotated their segments and oscillated more in searching than free-viewing and more in both tasks than in gaze-fixation. This study confirmed that precise visual tasks may require the brain to control synergistic relations between eye and body movements instead of individual eye and body movements.** 

**Key words: synergistic model, relations between eye and COP/body movements, cognitive involvement, young adults, performance.**

## INTRODUCTION

In the literature on postural control, when relations between vision and posture are examined, participants mainly move their eyes back and forth at an imposed amplitude and frequency between targets projected onto a white background (e.g., Stoffregen et al., 2006; Rougier and Garin, 2007; Stoffregen et al., 2007; Anastasopoulos et al., 2009; Bonnet and Despretz, 2012). Their body movements are thus also limited as they repeat the same pattern back and forth. However, in day-to-day life, individuals look at varied environments and move their body in unrestrained manners. The large disparity between real life and experimental conditions may be due at least to two main reasons. Firstly, if the participants were free to look anywhere they like in an experimental setting, investigators would be required to record and analyze both eyes and body movements. Secondly, if the participants were free to rotate their body as they pleased in various tasks, the interindividual variability of behaviors would be very high, with some participants rotating parts of their body (head and/or shoulder and/or lower back rotations) a great deal and rapidly, while other participants would move just a little and/or slowly. In such circumstances, comparing the amount of body movement in various conditions – as is typical in the literature on postural control (see Bonnet and Baudry, 2016a for a review and further details about existing models) – may be irrelevant. To reduce the disparities in this field of research, we performed a study in which the participants performed unrestricted eye and body movements by looking at complex large ecological images. We analyzed the strength of interrelations between eye movements and measures of body movements (head, neck, lower back, and center of pressure (COP) movements) in visual tasks of various cognitive difficulties to test the synergistic model of postural control (Bonnet and Baudry, 2016b).

*Corresponding author. Tel.: +33 320 446281; fax: +33 320 446732.
E-mail address: cedrick.bonnet@chru-lille.fr (Cédrick T. Bonnet).

[1] It is indeed true that body rotations can lead to greater linear body oscillations but this is not systematic. The synergistic model is not concerned by causes of linear body oscillations but by the existence of more or less body oscillations.

*Abbreviations:* COP, center of pressure; CNS, central nervous system; NASA-TLX, National Aeronautics and Space Administration Task Load Index; AP, anteroposterior; ML, mediolateral; R, range; SD, standard deviation; V, velocity; px, pixels.

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The synergistic model (Bonnet and Baudry, 2016b) is concerned with the adaptation of postural control to succeed in precisely shifting gazes in an upright stance. Our model is not concerned with the coordination of body segments to perform any types of tasks, i.e., it is not concerned with relations between angular variables measured at various levels of the body as in many other studies (e.g., Freedman and Sparks, 1997; Hollands et al., 2004; McCluskey and Cullen, 2007; Anastasopoulos et al., 2009). It focuses on the amount of COP and/or body movement to perform precise vs. unprecise gaze shifts.[1] The term 'synergy' does not refer to a group of muscles working together but rather to "only" eye and COP/body movements – hereinafter referred to as COP/body movement – which are supposed to function in a complementary way. The term 'eye movement' refers to kinematics of eye movements when performing fixations and saccades to explore a visual display.[2] The terms precise and unprecise gaze shifts refer to sequential self-directed goal-oriented gaze shifts and sequential gaze shifts without a predefined goal, respectively. In our model published (Bonnet and Baudry, 2016b), we suggested that in precise visual tasks, the central nervous system (CNS) may control both eye and COP/body movements in relation to one another, i.e., in a synergistic manner, to succeed in these tasks. In contrast, in unprecise visual tasks, the CNS may simply control the eye and COP/body movements separately, with no synergy, and thus with a basic level of cognitive involvement. In our view, synergies may not be required in unprecise tasks (Bonnet and Baudry, 2016b).

A recent study validated the two main hypotheses of the synergistic model. In Bonnet et al. (2017), 16 healthy young adults performed (precise) search and (unprecise) free-viewing visual tasks in looking at small images (22° of visual angle). In the search task, the participants were asked to locate a target within an image in which there were a lot of details. The task proved very difficult. In this study, the results showed only negative eye–body (head, neck) correlations in the search task and only positive eye–COP/body relations in the free-viewing (control) task. The negative relations were described as synergistic because they showed better control of body posture – i.e., a lower level of postural sway – when performing significantly larger eye movements. We should emphasize that a lower amount of postural sway in one task relative to the control task is generally assumed as a sign of better postural control, or better functionality of postural control (e.g., Mitra, 2003; Mitra et al., 2013; Blaszczyk et al., 2016). Negative correlations between eye and COP/body movements thus could be assumed as functional because the larger the eye movements, the more stable the participants. This reduction of postural sway may be functional because it may facilitate success in performing precise gaze shifts and minimize the level of useless, and even perturbing (Mitra, 2003), optic flow generated by postural sway. In contrast, the positive eye–COP/body relations could not be referred to as functional relations but instead as destabilizing relations, since larger eye movements were associated with larger postural sway (e.g., Bonnet and Despretz, 2012). In the literature on postural control, it is indeed generally assumed that a greater amount of postural sway in one task relative to the control task is synonym of lower postural stability (e.g., Mitra, 2003; Mitra et al., 2013; Blaszczyk et al., 2016). In the present study, one initial question of interest was to discover whether functional stabilizing eye–COP/body relations could be found during a search task requiring large ecological gaze shifts instead of small ones, and whether they can exist when the body moves in unrestrained manners instead of being constrained to stand as still as possible. These questions are important because eye, head, upper body and lower body movements are rarely limited to small amplitudes (<22°) in everyday activities.

A second question of interest was to analyze the influence of a superimposed cognitive task on the quantity of eye–COP/body correlations in both search and free-viewing tasks. Previous investigations have mainly studied the influence of a cognitive task on postural sway and/or postural control (Dault et al., 2001; Hunter and Hoffman, 2001; Maylor et al., 2001; Pellecchia, 2003; Swan et al., 2004; Broglio et al., 2005; Chong et al., 2010; Resch et al., 2011; Mudjdeci et al., 2016) but not the influence of cognitive tasks on the relations between eye and COP/body movements. In our view, the act of performing a very hard cognitive task in addition to a precise visual task should require even more functional eye–COP/body movement relations than performing a precise visual task with no added cognitive task. We argue that the CNS would need to stabilize the visual field even more in this triple task[3] (precise visual task + postural control + added cognitive task) than in the double precise visual task, to avoid even more visual perturbations – optic flows – that can distract from both performances. At an empirical level, individuals do indeed prefer to maintain a stable visual environment when performing complex cognitive tasks instead of shaking their head and eyes everywhere.

The study's objective was to test the validity of the synergistic model when the participants performed large ecological gaze shifts, either alone or in addition to a cognitive task. Sixteen healthy young adults performed six conditions

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[2] For a full definition of the synergistic model, please refer to Bonnet and Baudry (2016b).

[3] The term "double task" was chosen over the term "dual task" because "dual task" refers to the conceptual argument that the CNS has to divide its attention (notion of "duality" or conflict). In the synergistic model, there is no duality or conflict between tasks but instead synergy or unity. Hence, we cannot use the term "dual tasks" if we assume – as in the present study – that there should be more synergistic eye–COP/body relations when combining both the search and the counting tasks, i.e. in the double task, than in the single search task. In this instance, using the term "dual task" would not make sense at a theoretical level. Instead, the term "double task" is neutral at the theoretical level because it simply states that two tasks are performed simultaneously.

combining three visual tasks (free-viewing, search and gaze-fixation) and two contrasted counting tasks (backward counting vs. no counting). The first hypothesis proposed that we would find significant negative and positive eye–COP/body correlations in searching and free-viewing respectively. This result would be similar as in Bonnet et al. (2017) but this time in tasks requiring large ecological gaze shifts and no constraint for body motion. The second hypothesis proposed that the CNS may need to engage more subjective cognitive involvement, i.e. cognitive workload (Hart and Staveland, 1988), in searching than free-viewing (cf. Bonnet et al., 2017). In other words, the search task was supposed to be perceived as more difficult. In addition, we expected the subjective cognitive engagement to be higher in the search–counting task (when the search and counting tasks were performed together) than in the search and/or counting task performed alone. It turns out that the performance at counting the number of targets should be lower in the search–counting task than in the search task performed alone because less cognitive resources would be available for searching to detect the targets when also counting in one's head. Our third hypothesis proposed that the triple task (searching and counting upright) would require a higher number of significant negative eye–COP/body correlations than simply searching upright.

## EXPERIMENTAL PROCEDURES

### Participants

Sixteen healthy students (eight males, eight females) from the University of Lille were included. Their mean age, body-weight and height were 19.8 ± 1.6 years, 64.6 ± 10.2 kg and 173.3 ± 7.3 cm, respectively. The participants were included because they had good or suitably corrected visual acuity (based on a question the participants were asked). They were excluded if they were not healthy, i.e., if they were affected by a disease or an injury that could interfere with postural control (e.g., a foot injury). The study was approved by the local independent ethics committee at our university. The participants gave their written, informed consent to participate.

### Apparatus

A magnetic tracking system (Polhemus Liberty 240/8-8 System, Colchester, VT, USA), a dual-top force platform (AMTI, Watertown, MA, USA) and a head-mounted eye tracker (SensoMotoric Instruments, Teltow, Germany; Fig. 1B) were used to record the movements of three markers (sampling frequency: 240 Hz), of the COP (sampling frequency: 200 Hz) and of the participants' right eye movement (sampling frequency: 50 Hz). The Polhemus markers were positioned at the occiput (head marker, on a helmet), at the seventh cervical vertebra (neck marker) and at the fifth lumbar vertebra (lower back marker, on a belt). The foot position was standardized with a stance width of 14 cm and a stance angle of 17° (McIlroy and Maki, 1997). A MATLAB custom script (written with MATLAB 7.10 software, The MathWorks, Natick, MA, USA) was used to synchronize all apparatus. This script started and stopped all recordings at the same time.

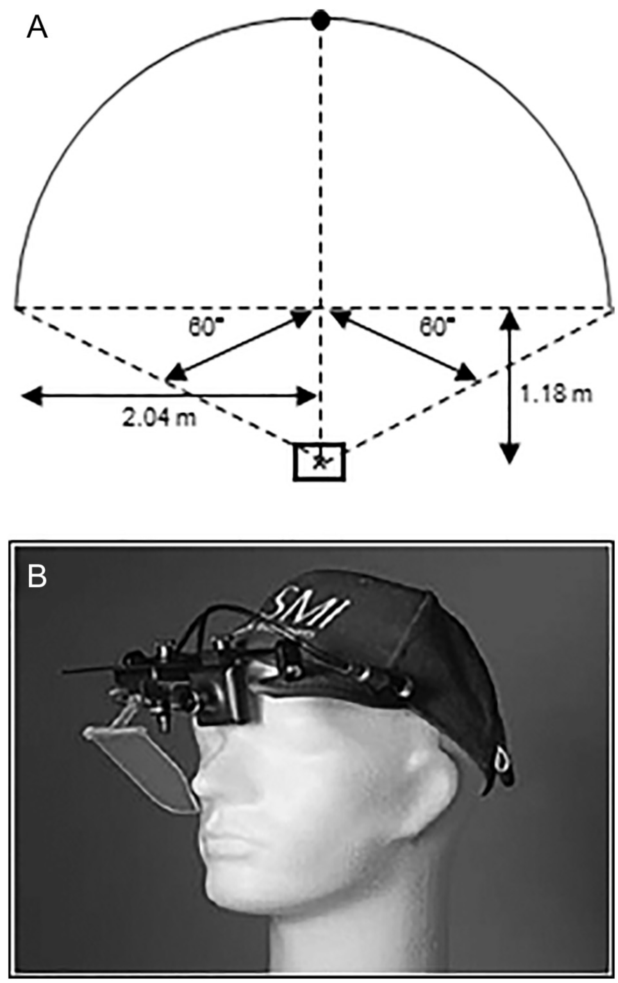


**Fig. 1.** (A) Figure showing the position of the participants with respect to the semicircular panoramic display (2.04 m radius, 2 m high). The participants stood 1.18 m behind the center of the display (they were located on the cross above the force platform represented by a rectangle) and the images therefore subtended a visual angle of 120°. (B) Image of eye-tracker used in the present study to record eye movements.

The participants stood in front of a semicircular, panoramic display (2.04 m radius, 2 m high) (Fig. 1A). Three video projectors (Optoma HD83, London, United Kingdom) were used to project the images onto the display. The participants stood 1.18 m behind the center of the display to view the images with a visual range of 120° left/right and 23° up/down, respectively. To fully explore the images, the participants needed to rotate their eyes, head, shoulders and possibly their lower back (Proudlock and Gottlob, 2007; Sklavos et al., 2010).

During the study, 12 images of natural landscapes (one per trial) were projected in front of the participants (e.g., a forest, a lake, a beach; see Fig. 2A). For each participant, six images were displayed in the search task and six more images were displayed in both the gaze-fixation and free-viewing tasks. In the search task, 10 animals were added to each image (the same animal displayed 10 times in the image). The animals were added randomly everywhere in the image and they were all displayed in the same orientation

**Fig. 2.** (A) Two of the 12 images projected onto the semicircular panoramic display and explored by the participants during the study. (B) On the left, an image of an animal (here a squirrel), as shown to the participants before each search trial. On the right, a small image of a natural landscape including many depixelized squirrels. (C) On the left, a small portion of an experimental image with no addition of a depixelized plant. On the right, the same small image including the addition of a depixelized plant.

but with varied sizes. They were consistent with the image, i.e., no crocodiles were displayed on a mountain landscape. In the free-viewing task, the images did not show any animals to avoid the participants searching for them. The participants knew there would be no animal in the images of the free-viewing task.

The 10 animals displayed in the search task were depixelated using Chu et al. (2010) to make the search task more difficult (see Fig. 2B). The TouchDesigner software (Derivative, Toronto, Canada) was used to determine the number of px (pixels) added in these images with the presence of the 10 animals. Subsequently, depixelated plants were added in the images for the free-viewing and gaze-fixation tasks to have the same number of px in the corresponding images (see Fig. 2C). Photoshop CS6 (Adobe Systems, San Jose, USA) and PhotoFiltre 7 (Freeware, Antonia Da Cruz) were used to modify the plants added to these images.

A questionnaire quantified the cognitive involvement in each task. As in Bonnet et al. (2017), the validated French version (Cegarra and Morgado, 2009) of the National Aeronautics and Space Administration Task Load Index was used (NASA-TLX; Hart and Staveland, 1988). The NASA-TLX was chosen because i) it is sensitive to fine variations between tasks (Cegarra and Morgado, 2009), ii) it has been validated hundreds of times (Hart, 2006) and iii) it has shown excellent reliability, sensitivity and utility (Hart, 2006).

## Conditions and instructions

The participants performed six conditions combining two types of cognitive task (a counting task and a non-counting task) and three types of visual task (gaze fixation, free-viewing and search). In all trials, the participants were told to relax and hold their hands by the side of their body. They were asked to avoid any voluntary movements (e.g., hand movements) other than those necessary to perform the tasks.

The cognitive task consisted of counting backward in one's head from a three-digit number (e.g., 729) subtracting seven each time until the end of the trial. The participants were given instructions to perform the counting task as accurately as possible (primary requirement) with as many subtractions as possible (secondary requirement). At the end of each task, the experimenter asked the participants what final number they had reached and gave feedback to the participant on whether the reported number was right or wrong. If the participant was wrong, the experimenter invited him/her to be more careful about this task in the next trials.

In each trial, the participants had to fixate the black cross for the first 3 s. This black cross was displayed in front of the participant at the center of the display and it was surrounded by the experimental image. In the gaze-fixation task, the participants had to fixate this black cross for the duration of the trial (53 s) while standing quietly. In the free-viewing and search tasks, once the cross disappeared (after 3 s), the participants were free to explore the image as they liked until the end of the trial. They could do so by moving their head, shoulders and lower back if necessary. One constraint was that they had to constantly look at the image through the small window of the eye-tracker (diameter of that window: 40°; Fig. 1B) so that the eye movement could be recorded at all times. When searching, the participants had to stare at the animal found for 3 s to validate their finding, i.e., they had to stare at it sufficiently long to enable the investigator to credit/count the performance.[4] After each trial in the search task, the investigator asked the participants how many animals they had found and how confident they were about their performance (1/5 being the lowest rate and 5/5 being the highest).

During each trial in the search task, the participants had to retain the number of animals they had counted and tell that number to the investigator at the end of the trial. If the number of animals supposedly found by the subjects – according to their estimation – was different than the number of animals counted by the investigator (assessed from the online video of the eye tracker), a discussion was attempted to elucidate the cause of this difference. After each trial in the search task performed conjointly with the counting task, the participants had to tell the investigator how many animals they had found and what number they had reached in the subtraction task.

In the search task, the requirement of counting the number of animals found in the image in one's head could have a confounding effect. Indeed, the participants were searching and counting the number of animals in one task while they were not doing either of these two tasks in the free-viewing task. To control and avoid this cognitive bias, the participants were given instructions to count very slowly, beginning with the number 1 and ending up with a number between 5 and 10 in the free-viewing and gaze-fixation tasks and to tell the investigator which number they had reached at the end of the trial. Failure was recorded if the participants did not count at all or counted beyond 10.

In the search task, the participants performed two types of eye movement, a visual search (when searching for the animals) and a gaze-fixation task (when staring at the animal found for 3 s). This problem was known a priori but we could not ask the participants to say something aloud each time they found an animal. Indeed, speech is known to change postural control (Yardley et al., 1999). To control this issue, the data (eye and COP/body movements) for the short periods when the participants stared at an animal were deleted a posteriori.

The images in the free-viewing and search tasks were different to avoid the participant seeing the same images twice. To control the main effect of the images, half of the participants watched images 1–6 for free-viewing and images 7–12 for searching (Group A) and the other half of the participants watched images 7–12 for free-viewing and images 1–6 for searching (Group B). Half of the participants in both groups (A and B) performed the single visual task (search, free-viewing or gaze-fixation) during the first three trials and performed the triple tasks (visual + posture + cognitive) during the last three trials and the other half of the participants performed these tasks in the reverse order.

Acronyms were used to simplify the name of the experimental tasks. For example, the 'search–counting' task corresponded to the combination of the search and counting tasks while the single terms 'search' and 'counting' tasks corresponded to the search task and counting task performed in different trials.

## Procedure

Once the participants arrived in the experiment room, they signed the information and consent forms. The investigator displayed an image of a natural landscape on the panoramic display (a 13th image, which was never used during the study) to explain the three visual tasks. The first time this image was projected, it included 10 fully visible animals and the second time, it included the same 10 depixelated animals displayed at the same locations. Once the six tasks were explained, the investigator invited the participants to read and understand the NASA-TLX questionnaire. Next, the participants took their shoes off and were prepared (the helmet with the eye tracker and the three Polhemus markers were fitted). Calibration of the various devices was performed. The six tasks were performed one after another so that the participants could fill out the NASA-TLX questionnaire after each task when they sat on a stool. Specifically, in the search task and before each trial, an isolated image of the target animal was presented to the participant on the display screen for about 5 s so that they knew which animal they would have to search for. After each trial, the investigator asked i) the number of animals found and the confidence score in search or ii) the final number reached in counting backward, and/or iii) the control number reached in free-viewing and gaze-fixation.

## Preparation of the data

The first 3 s of data in each trial was not analyzed because the participants performed the same initial fixation task. The data of the force platform and of the Polhemus systems were resampled at 50 Hz in conjunction with the data of the eye tracker. The data of the eye tracker were not fully available for three reasons. Firstly, the participants sometimes did not look through the small window of the eye tracker, especially when they looked to the extreme right or left of the panoramic display. At these times, the eye position and movement were lost, i.e., 0-value was recorded in the data file. Secondly, no value was recorded when the participants blinked. Thirdly, and most importantly, with the light turned off, the eye tracker could lose the pupil position due to increased pupil dilatation. MATLAB scripts were constructed to delete the spurious 0-values and artifacts in the visual files. These scripts also deleted the corresponding behavioral data in the COP and Polhemus data files. For our main eye–COP/body correlations and the analyses of eye movements, only experimental trials with more than 80% valid eye movement data were retained. This criterion was used to analyze only good quality data.

Box plots were used to identify the presence of outliers. These box plots directly showed with a star on the graph extreme values considered as outliers. By definition, an outlier is a value differing from all other values in a particular group or set. In our study, we considered outliers in the tables of dependent variables found for each trial in each task and not in the time-series themselves. These spurious values

[4] The investigator could see online what the participants were looking at (on the video of the SMI software).

were deleted as recommended by Tabachnick and Fidell (2013). Then, the remaining values for each trial in each task were averaged for statistical analyses. Before performing these analyses, we tested normality and equal variances in our sample distributions and the data that did not meet these criteria were not considered.

## Dependent variables

### *COP and/or body movement*

The linear movement of the COP and/or body in an upright stance was analyzed on both anteroposterior (AP) and mediolateral (ML) axes with the range (R), standard deviation (SD) and mean velocity (V) of the COP, head, neck and lower back movements. It was also analyzed with the path length or distance traveled by the COP and body marker during the trial. This last measurement was described as more global because it did not concern only one axis but any direction. The angular movement of the head, neck, and lower back was analyzed in the yaw (left/right) and pitch (up/down) directions to determine the extent to which the participants rotated their body segments. The body rotations were calculated in space and not relative to one another, i.e., they showed how much rotation was performed at each level with respect to the earth reference. Abbreviations were used to simplify the naming of the dependent variables. For example, '$R_{AP}$' corresponded to the range of linear movement on the AP axis and '$R_{yaw}$' corresponded to the range of angular movement in the yaw direction.

### *Eye movements*

For the eye movements, the characteristics of the time-series were analyzed in terms of R, SD, V and general path length. We also analyzed the characteristics of fixation (thus excluding the spatial characteristics of blink and saccade) when the eyes moved on the visual display to explore the images. The SMI software Begaze calculated the spatial and temporal distributions of the fixations performed in the full trials and we then analyzed whether these fixations were close to each other or spread out in terms of R, SD, V and general path length between fixations. Although both types of eye movement dependent variables (based on time-series and characteristics of fixation) may seem redundant (they indeed came from the same raw data), they did not provide the same information about eye movements. The spatial characteristics of the time-series showed where and how the eyes moved. They concerned the full time-series analyzed for 50 s. The characteristics of fixation were only the part of the data concerned with fixations, i.e. moments during which the participants kept their eyes at a certain location to identify aspects of the image. Therefore, although some variables were identical (R, SD, V) in both types of eye movement dependent variables, the results were different in both tables ready for statistics. Accordingly, we used both types of variable in Bonnet et al. (2017) and showed that these variables generated complementary, contrastive results between tasks.

The eye movement data were recorded in px and were not converted into degrees for two reasons. Firstly, we could not directly and easily convert the data into degrees because the participants did not stand in the middle of the panoramic display (Fig. 1A) and because their head moved during trials (as individuals swayed upright). Secondly, and most importantly, we did not need to convert the data into degrees because we only analyzed the extent to which the eyes moved, irrespective of what the participants looked at. We should have converted the data into degrees if we had analyzed what the participants looked at. Some data for the gaze-fixation task are reported in degrees because the approximation was possible for this task (not biased by the curvature of the panoramic display).

### *NASA-TLX*

The subjective cognitive engagement of each task was assessed using the NASA-TLX global score (Hart and Staveland, 1988; Cegarra and Morgado, 2009).

### *Performance in searching and counting*

To describe performance in the search task, the number of animals found, the percentage of failure/success and the confidence score were analyzed. A failure was counted when the participant i) did not fixate an animal but something other than an animal or ii) explained that he/she found *x* animals but did not fixate *x* animals (according to the investigator's assessment). To describe performance in the counting task, two variables were analyzed: accuracy (success/failure) and the number of successive subtractions performed in each trial.

## Statistical analyses

### *For the correlations between eye and COP/body movements*

The synergistic model can be tested with correlations between eye movements (spatial and temporal characteristics) and linear movements of the COP/body. The correlations can be performed only with mean values of the full time-series (e.g. R, SD, V). The model can also be tested in conjunction with eye–COP/body cross-correlations. In this respect, we first performed the cross-correlation on the full time-series, correlating each eye and COP/body variables one to another, to get one cross-correlation coefficient for each trial. Then, we compared the eye–COP/body cross-correlation coefficient of each participant in the various task with an ANOVA (see below for more details). The model uses linear instead of angular movement of the body segments because it focuses on the amount of COP and/or body linear movement, also called sway, when performing gaze shifts and not the way the various body segments rotate with respect to each other.

Pearson correlations were used to analyze linear relations between all variables of eye and body/COP movements. All the significant eye–COP/body correlations were then re-entered into a new analysis that controlled – or ruled out the possibility of having – the contribution of cognitive involvement on these eye–COP/body correlations. To this end, we used partial correlations with the three variables (eye movement, COP/body movement, cognitive involvement), the controlled factor being cognitive involvement. These partial correlations examined the significant correlations between eye and COP/body movement in controlling/suppressing the potential influence of the cognitive involvement on these correlations. Cross-correlations between eye and COP/body movements were used to find out if the eyes and COP/body moved simultaneously, i.e. in-phase or in anti-phase. We analyzed eight cross-correlations, that is between the eyes on one hand and the COP, head, neck and lower back on the other hand in both the mediolateral (body movement)/left–right (eye movement) and anteroposterior (body movement)/up–down directions (eye movement). All the correlations and ANOVAs were exploratory and performed with an adjusted $p$-value ($p < 0.01$). This alpha level was adjusted based on the test of several hypotheses and not on the number of correlations in the exploratory analyses, as suggested by Rubin (2017). Additionally, an ANOVA was performed on the NASA-TLX global score to test one of our main hypotheses ($p < 0.01$). All primary and secondary analyses were performed with Statistica 10 software (Statsoft Inc., Tulsa, OK, USA).

*For the secondary analyses*

In the introduction, we suggested that the comparison of the amount of eye–COP/body movement recorded in each task could not test the synergistic model and this is indeed correct. However, for complementary reasons, the amount of movement was analyzed with two-way ANOVAs to determine whether the participants rotated their eyes and body segments more extensively in one task than in another ($p < 0.01$). Post-hoc Newman–Keuls analyses were performed when the ANOVAs were significant ($p < 0.01$).

## RESULTS

### Selection and choices before analyses

*Selection of the experimental trials to analyze*

After deleting the files with less than 80% valid – analyzable – data, the remaining eye movement files contained, on average, 88.5 ± 5.2% valid data. Ninety-two files were deleted, comprising 32% of all the trials performed.

Preliminary analyses showed no outliers in the NASA-TLX global score and six outliers in all the tables of eye movements (two in the characteristics of fixation and four in the time-series of eye movements). Five of these outliers were found in the gaze-fixation tasks (4/5) and one in the free-viewing–counting task (1/5). For COP, there were 42 columns of data (7 dependent variables × 6 tasks) and we counted 12 outliers. For the three body markers, there were 378 columns of data (21 dependent variables × 6 tasks × 3 markers) and 65 outliers for all linear variables and 79 outliers for all angular variables. There were more outliers in gaze fixation (67 in total) than in free-viewing (53 in total) and in searching (36 in total). These outliers were deleted as explained earlier in the Method section.

*Methodology in the search task*

In our data set, only 12 fixations (found in eight different trials) were longer in the search task than the longest fixation in the free-viewing task. Therefore, the requirement to fixate the depixelated animal for 3 s did not seem to bias eye and COP/body movements. Consequently, instead of deleting the longest fixations each time the animal was found (see the Method section for more explanations), only these 12 longest fixations were deleted in the search trials. The corresponding data in each recorded file (eye and COP/body movements) were deleted.

### Correlation analyses between eye and COP/body movements

Table 1 shows the significant eye–COP/body correlations in searching and free-viewing. Nine negative and five positive correlations were found to be significant in the two search tasks and in the two free-viewing tasks, respectively. Table 1 shows that there was no significant Pearson correlation between eye movements and COP, neck movements in the search task and between eye movements and COP, lower back movement in the free-viewing task (empty cells). Four correlations were significant between eye and head movements in the search task and that five correlations were significant between eye and head, lower back movements in the search–counting task. Eight of nine of these significant correlations were found with spatial and temporal characteristics of fixation. Table 1 also shows four significant correlations between eye and head movements in the free-viewing task and one significant correlation between eye and neck movements in the free-viewing-counting task. Only one of five of these significant correlations was found with spatial and temporal characteristics of fixation. For the details of the dependent variables that were significantly correlated, see Table 1. One can notice that most of the significant correlations were found at the head (86% of the time, cf. Table 1).

As explained in the Method section, all Pearson correlations that were significant in Table 1 were performed a second time in controlling the influence that the cognitive involvement could have on the significant eye–COP/body correlations. When performing these partial correlations, 78% ($n$ = 7/9) and 80% ($n$ = 4/5) of the relations were no longer significant in both search tasks and in both free-viewing tasks, respectively (cf. Table 1, results in bold). Controlling for the influence of the NASA-TLX global score withdrew the significant relation between eye and COP/body movements 100% of the time in both search–counting and free-viewing. When the partial correlations were not significant anyone (while the eye–COP/body correlations were significant), it meant that change in the cognitive involvement could have – were supposed to have – a significant influence on the existence of the eye–COP/body correlations. In contrast, when the partial correlations were not significant, the cognitive involvement had no influence on the eye–COP/body correlations.

None of the eight ANOVAs for the cross-correlations were significant ($F_s < 0.67$, $p > 0.01$).

**Table 1. .** Significant relations (Pearson correlations) between eye movement and movement of the center of pressure (COP), head, neck and lower back (non-significant correlations are not reported in the Table below). In each cell of the Table below the eye movement variables are always written first and the COP/body movement variables are written second (before giving the correlation coefficient in parentheses). Table 1 also reports the results of the partial correlations. The lines in bold are important because they show the Pearson correlations that were not significant anymore when the NASA-TLX global score was controlled. In fact, all the significant Pearson correlations found below were performed again but this second time in controlling the influence that the NASA-TLX global score could have on the significant correlations between COP and/or body movements. It turns out that the correlations in bold (between COP and/or body movements) would not have been significant if the NASA-TLX global score had not changed ($p > 0.01$).

| | Tasks performed without counting (no-counting task) | Tasks performed in counting (counting task) |
|---|---|---|
| Eye movement and COP movement in the search task | / | / |
| Eye movement and head movement in the search task | **R up/down of fixation and Vhead AP ($r = -0.72$)**<br>SD up/down of fixation and Vhead AP ($r = -0.79$)<br>**Number of fixations per min and Vhead ML ($r = -0.71$)**<br>SD up/down of time-series and Vhead AP ($r = -0.69$) | **Number of fixations per min and Vhead AP ($r = -0.73$)**<br>**Number of fixations per min and Vhead ML ($r = -0.73$)**<br>**Number of fixations per min and path length head ($r = -0.72$)**<br>**SD up/down of fixation and Rhead AP ($r = -0.81$)** |
| Eye movement and neck movement in the search task | / | / |
| Eye movement and lower back movement in the search task | / | **Relative duration of fixation per min and V lower back AP ($r = -0.72$)** |
| Eye movement and COP movement in the free-viewing task | / | / |
| Eye movement and head movement in the free-viewing task | **Path length of time-series and Vhead AP ($r = 0.76$)**<br>**Vhead left/right of time-series and Vhead ML ($r = 0.76$)**<br>**Path length of time-series and Vhead ML ($r = 0.73$)**<br>**Path length of time-series and path length head ($r = 0.76$)** | / |
| Eye movement and neck movement in the free-viewing task | / | SD up/down of fixation and path length neck ($r = 0.69$) |
| Eye movement and lower back movement in the free-viewing task | / | / |

*Note.* For the eye movements, the dependent variables concerned the range amplitude (R), the standard deviation (SD) and mean velocity (V) in the left/right and up/down directions of the eye movement time-series. Another group of eye movement dependent variables concerned the characteristics of fixation, i.e. the number of fixations per minute, the relative duration of fixation per minute and also the same variables as for the eye movement time-series (R, SD, V in the left/right and up/down directions) (see Method section for the distinction between these variables). For the center of pressure and markers (head, neck, lower back) displacements, the dependent variables were R, SD and V on the mediolateral (ML) and anteroposterior (AP) axes as well as the path length of displacement. See the manuscript for more details about these dependent variables.

## Secondary analyses

### *Performance in searching and counting*

*Performance in searching.* The participants found significantly more targets in searching (7.6 ± 0.8) than in search–counting (6.6 ± 0.9; $t(15) = 3.5$, $p < 0.01$). At most, four participants found the 10 animals in searching and three participants found nine animals in search–counting (never 10).

*Performance when counting backwards in 7 s.* On average, the success rate for counting was equivalent in the three visual tasks (fixation: 66.7%; free-viewing: 66.7%; search: 68.8%). However, the number of subtractions was significantly lower in searching (6.7 ± 3.0) than in both free-viewing (10.3 ± 7.1) and gaze fixation (11.3 ± 7.8) ($F(2,30) = 16.4$, $p < 0.01$).

*Control performance.* When the participants simply had to count slowly from 1 to 5–10, there were only one failure (see Methods section) in both free-viewing tasks (success: 97.9%) and two failures in both gaze-fixation tasks (success: 95.8%).

### *NASA-TLX*

The ANOVA showed significant main effects of counting ($F(1,15) = 75.0$, $p < 0.01$) and visual task ($F(2,30) = 7.7$, $p < 0.01$; Fig. 3). The post-how analyses showed that the NASA-TLX global score was significantly higher in counting than in non-counting and in searching than in free-viewing ($p < 0.01$; Fig. 3). The post-hoc analyses did not show any difference in the subjective cognitive engagement between the three visual tasks performed both in counting and in non-counting tasks ($p > 0.01$).

### *Dependent variables for the eye movements*

*Dependent variables calculated in the time-series of the eye movements in the two gaze-fixation tasks.* There was no significant difference in the performance of gaze fixation in both fixation and fixation–counting tasks ($p_s > 0.01$). The variability in eye movements in both tasks was as follows: $R_{left/right}$: 2.2 ± 0.2°; $R_{up/down}$: 5.2 ± 0.6°; $SD_{left/right}$: 0.4 ± 0.0°; $SD_{up/down}$: 10.0 ± 0.1°.

*Dependent variables calculated in the time-series of the eye movements in the free-viewing vs. search*

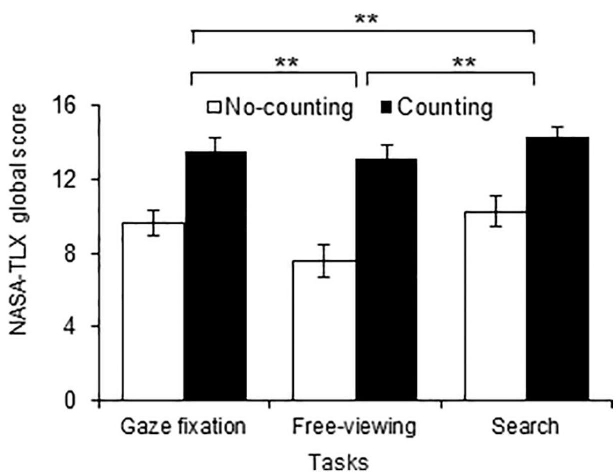


**Fig. 3.** Figure showing the NASA-TLX global score in the six experimental tasks. In these tasks, the participants either counted backward (counting) or did not count (no-counting) and they either looked at a stationary cross or explored images of natural landscapes during the trial (see text for more details). Means ± standard error of the means are shown. The ANOVA showed a significant main effect of counting and of visual tasks. For this second main effect, the post-hoc Newman–Keuls showed that NASA-TLX global score was significantly higher in the search tasks than in the gaze-fixation tasks and significantly higher in both previous tasks than in the free-viewing tasks. We indicated these significant effects with three horizontal lines above the graph (** indicated $p < 0.01$).

*tasks.* The ANOVAs did not show any significant difference between the free-viewing and search tasks (*ns*).

*Characteristics of fixation (calculated from the SMI Begaze analysis software) in the free-viewing vs. search tasks.* For the range of up/down fixation, the ANOVA showed a significant visual tasks × counting interaction effect ($F(1,11) = 17.2$, $p < 0.01$). $R_{up/down}$ lowered from free-viewing (mean: 249 ± 34 px) to free-viewing–counting (mean: 175 ± 21 px) while it remained constant from searching (mean: 216 ± 57 px) to search–counting (mean: 217 ± 37 px). For the SD of up/down fixation, the ANOVA showed a significant main effect of counting ($F(1,8) = 12.2$, $p < 0.01$) and a visual task × counting interaction effect ($F(1,8) = 23.3$, $p < 0.01$). $SD_{up/down}$ lowered from free-viewing (mean: 56 ± 8 px) to free-viewing–counting (mean: 36 ± 6 px) while it increased from searching (mean: 46 ± 13 px) to search–counting (mean: 49 ± 8 px). The above results in pixels are difficult to interpret. However, as the glass of the eye tracker covered 480 px up/down for 42°, the $R_{up/down}$ and $SD_{up/down}$ turned approximately 18° and 4° in both tasks, respectively.

## Body movements and rotations

*Maximum rotations of the body parts (in range) to explore the images in the free-viewing and search tasks*

In the yaw direction, the participants turned their head-in-space up to 77° and 62° in the search and free-viewing tasks respectively (Appendix A). In the pitch direction, the rotations of the body segments were small, i.e. 8° and 6° in searching and free-viewing respectively (cf. Appendix A).

*Angular and linear movements in the three tasks*

Angular and linear movements contrasted in the gaze-fixation task vs. both other (free-viewing and search) tasks. Appendix B shows that the participants rotated their body parts and swayed significantly more in free-viewing and searching than in gaze-fixation for almost all dependent variables. However, the participants did not move more quickly and did not exhibit a more extensive path length in free-viewing and searching than in gaze-fixation at the COP ($V_{AP}$, $V_{ML}$, path, $F_s(2,30) < 0.8$, $p > 0.01$) and neck levels ($V_{AP}$, $V_{ML}$, linear path, $V_{pitch}$, $F_s(2,30) < 5.4$, $p > 0.01$).

*Angular movement between the free-viewing and search tasks.* The head $R_{yaw}$, neck $R_{yaw}$, head $R_{pitch}$ and lower back $R_{pitch}$ were significantly higher in searching than in free-viewing (Appendix B; post-hoc Newman–Keuls analysis, $p < 0.01$). All these effects showed that the participants rotated their body segments more for searching than for free-viewing. One remarkable effect of counting was also found for the head $R_{pitch}$ ($F(2,30) = 9.9$, $p < 0.01$; Fig. 4A). The participants rotated their head-in-space less in the up/down direction in the counting task than in the non-counting task (Fig. 4A).

*Linear movement between the free-viewing and search tasks.* The head $R_{AP}$, the lower back $R_{AP}$ and $R_{ML}$ were significantly higher in searching than in free-viewing (cf. Appendix B; post-hoc Newman–Keuls analysis, $p < 0.01$). The participants exhibited more extensive body movements in searching than in free-viewing. There was no significant main effect of counting (*ns*). However, a significant task × counting interaction effect was found for the head $R_{ML}$ ($F(2,30) = 10.3$, $p < 0.01$; Fig. 4B). The participants reduced their head $R_{ML}$ from free-viewing to free-viewing–counting while they increased them from searching to search–counting.

## DISCUSSION

In the present study, our main objective was to test the validity of the synergistic model when participants performed visual tasks that required large and free ecological gaze shifts. The results convincingly showed that the participants adopted functional eye and body relations, or eye–body synergies in precise visual tasks. As expected, the search–counting task engaged more functional, stabilizing, eye–body relations than the search task alone. Instead, in both free-viewing tasks, the participants displayed inverse (positive, destabilizing) eye–COP/body correlations. The simple fact of counting vs. not counting did not change the eye–COP/body relations in the free-viewing–counting tasks. In the discussion below, we also report that the significant correlations between eye and body movements were mainly related to higher cognitive involvement in searching while they were related to lower cognitive involvement in free-viewing.

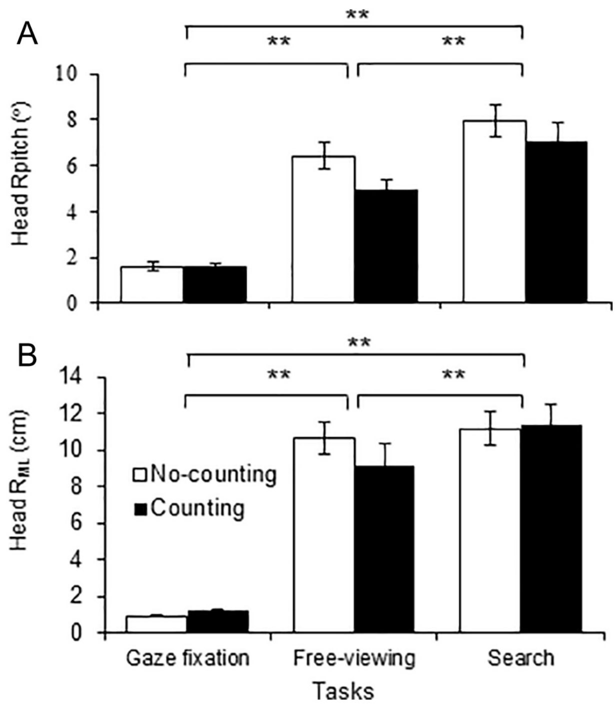


**Fig. 4.** Figures showing one angular and one linear dependent variable of the head movement in the six experimental tasks. In these tasks, the participants either counted backward (counting) or did not count (no-counting) and they either looked at a stationary cross or explored images of natural landscapes during the trial (see text for more details). Means ± standard error of the means are shown. (A) The maximum excursion, or range (R), of the pitch movement (up/down) of the head (in degrees, °). The ANOVA for head Rpitch showed a significant main effect of counting and of visual tasks. For this second main effect, the post-how Newman–Keuls showed that the head Rpitch was significantly higher in the search tasks than in the free-viewing tasks and significantly higher in in both previous tasks than in gaze fixation tasks. (B) The range of the head movement on the mediolateral (ML) axis (in centimeters, cm). The ANOVA for head $R_{ML}$ showed a significant main effect of visual tasks. The post-hoc Newman–Keuls showed that head $R_{ML}$ was significantly higher in the search tasks than in the free-viewing tasks and significantly higher in both previous tasks than in gaze fixation tasks. We indicated the significant effects in A and B with the three horizontal line above the graph (** indicated $p < 0.01$). A significant visual task × counting interaction effect was also found for the head $R_{ML}$ (not represented on the Figure yet).

## Definition of the synergistic model

This study tested a recent model concerned with the adjustment of postural control to succeed in precise visual tasks performed in an upright stance. In our model, we predicted that the completion of precise visual tasks should require the existence of functional eye–COP/body relations (Bonnet and Baudry, 2016b). In contrast, we expected the potential absence of functional eye–COP/body relations in unprecise visual tasks. For recall, the model is concerned with relations between eye movements (measured in angular terms) and COP/body movements (measured in linear terms).

## Functional eye–COP/body relations in searching

The negative eye–COP/body correlations found in the two search tasks (Table 1) seemed to be functional because they showed that the more the eyes moved, the less the body swayed. By only finding negative correlations in the search task (Table 1), we were able to validate our main hypothesis. We recall our initial insight that a lower amount of postural sway is generally assumed as a sign of better postural stability, i.e. better functionality of postural control (e.g., Mitra et al., 2013; Blaszczyk et al., 2016). Negative correlations between eye and COP/body movements thus could be assumed as functional because the larger the eye movements, the more stable the participants were. These negative correlations were especially functional because they involved postural stability at the head level (8/9 correlations, Table 1), which is a part of the body close to the eyes. Therefore, in precise visual tasks, even when large ecological gaze shifts were performed, postural stability was required to perform precise gaze shifts. These results were also functional because they were found 89% of the time ($n$ = 8/9) with characteristics of fixations (Table 1). As such, the CNS needed to attain certain specific zones of fixation and therefore engaged eye–COP/body synergies to do so. The number of functional eye–body relations between the search–counting vs. search tasks (negative correlations) was approximately the same ($n$ = 4 vs. $n$ = 5) but the cognitive involvement had a greater effect in search–counting (in 100% of the significant correlations) than in searching (in 50% of the significant correlations) (Table 1). In brief and to be clear, negative correlations between eye–COP/body movements showed stabilizing relations. Therefore, Table 1 confirmed our hypothesis that both searching and search–counting tasks required stabilizing relations between eye and body movements to succeed in the precise visual task. These stabilizing relations required a significant increase in subjective cognitive workload to exist, especially in the search–counting task (Table 1).

In the free-viewing tasks, the results only showed positive eye–COP/body relations and were more numerous in free-viewing ($n$ = 4) than in free-viewing–counting ($n$ = 1). These tasks therefore engaged destabilizing relations. In contrast to the search tasks, almost all of these significant correlations were found with time-series of eye movement and not with characteristics of fixation (Table 1). Overall and as in our previous study performed on a small visual display (Bonnet et al., 2017), we can definitely suggest that free-viewing tasks 1) do not require functional, stabilizing eye–COP/body relations and 2) do instead lead to destabilizing relations. These positive correlations are interpreted as destabilizing because an increase in postural sway is systematically associated with less stability, never with a better stability, in the literature on postural control (e.g., Mitra et al., 2013; Blaszczyk et al., 2016). Unexpectedly, the four significant positive correlations in free-viewing all disappeared when partialling out the influence of the cognitive involvement in these correlations (Table 1). As a first insight, this finding could be interpreted as showing that the CNS engaged more cognitive involvement to push the visual–postural system toward more instability in free-viewing. This interpretation is surprising, non-sense. We need to take into account the fact that the NASA-TLX global score was significantly lower in free-viewing than searching and even slightly lower in free-viewing than in the other basic task (free-viewing: 10.35 ± 4.42; gaze fixation: 11.55 ± 3.54). Hence, a second interpretation is that in free-viewing, these significant correlations between eye and body movements were related to lower cognitive involvement in free-viewing and therefore meaningless.

Another important result in the present study is the distinctive role of the subjective cognitive engagement in free-viewing-counting vs. both searching-counting and searching. We need to mention that the NASA-TLX global score was not significantly different in these three tasks and that counting did not induce, by itself – in the free-viewing-counting task – negative eye–COP/body correlations. Hence, the subjective cognitive engagement was identical in these three tasks but, it did not serve the same purpose. In search–counting and searching, the subjective cognitive workload served to link eye and body movements while it did not have such a role in the free-viewing-counting task. This result also validates the main hypothesis of the synergistic model because it shows that the CNS only needs the eye and body movement systems to work together in precise visual tasks and not in unprecise (e.g., counting) tasks.

In the present study, we found an equivalent number of significant negative and positive eye–COP/body correlations in searching and in free-viewing (four vs. four and four vs. four significant findings) as in our former study performed on a small visual display (Bonnet et al., 2017). These very similar results may be due to the fact that the participants moved their eyes and body slowly, or at least never quickly, back and forth, to perform both free-viewing and search tasks (cf. Appendix A). Consistently, considering that they moved their head-in-space on average 6–7$^{\circ.s^{-1}}$ in yaw in the free-viewing and search tasks (Appendix A), in average they needed more than 10 s to cover 60° to 80° (Appendix A) from the left to the right parts, which is a very long duration.

## Cross-correlations between eye and COP/body movements

We also studied cross-correlations between eye and COP/body movements. The results failed to demonstrate stronger cross-correlation coefficients between eye and COP–body movements in searching than in free-viewing ($r_s < 0.25$). Hence, the eye–COP/body synergies in precise visual tasks (Bonnet and Baudry, 2016b) may not be found by means of cross-correlation analyses but only by means of Pearson correlation analyses (Table 1). A posteriori, we could explain these results in suggesting that the eyes have a negligible mass while the body is heavy and needs time to move. When the eyes reach certain locations very quickly, postural sways should increase after these eye movements are performed, not before. Furthermore, the larger the body rotations, the longer the delay should become between angular eye and linear COP–body movements. Supposedly therefore, the further away the body moves the weaker the cross-correlation coefficients between eye and linear COP/body movements should become. In the present study, this reasoning could explain our low cross-correlation coefficients ($r_s < 0.25$) as our participants performed large gaze shifts in both searching and free-viewing.

## Cognitive difficulty of the three tasks

The results validated our hypotheses that the search task performed alone would be significantly more difficult that both free-viewing and gaze-fixation tasks performed alone. They also validated that the three counting tasks would be more difficult that the three non-counting task (Fig. 3). These results indirectly sustain our general hypothesis that the significant negative eye–body movements in searching (Table 1) require additional cognitive involvement to exist. Surprisingly, at the subjective level, the search–counting task was not found to be more difficult than the two other counting tasks (free-viewing–counting and fixation–counting). However, at the objective level, the performance in the number of successive subtractions was significantly lower in the search–counting task (6.73 ± 3.04) than in the free-viewing–counting task (10.26 ± 7.12), thus confirming our original hypothesis. The search–counting task was objectively more difficult than the two other counting tasks (free-viewing–counting and fixation–counting).

## Secondary results: Isolated behaviors (posture and vision alone)

In the gaze-fixation task, the participants did not rotate their body parts. In contrast, in searching and free-viewing, the participants needed to rotate their eyes (on average 45°) and their body parts (on average 77° and 62°, respectively; Appendix A) to fully explore the images. Rotations of heavy body segments such as the head necessarily have mechanical consequences on postural sway and other body rotations. This may be one reason why the participants swayed significantly less in gaze fixation than in both free-viewing and searching (Appendix B; Bonnet and Despretz, 2012).

The participants swayed significantly more on the AP and ML axes in searching and free-viewing than in gaze-fixation (Appendix B). These reports are important because they contrast with the literature, showing that young participants sway significantly less in precise search tasks than in gaze-fixation tasks when these tasks are performed on a small visual display (e.g.,Stoffregen et al., 2006, 2007 ; Rougier and Garin, 2007 ; Giveans et al., 2011 ; Rodrigues et al., 2013). In fact, when the participants did not, or were not allowed to, rotate their body parts (Stoffregen et al., 2006, 2007; Rougier and Garin, 2007; Giveans et al., 2011; Rodrigues et al., 2013), the CNS could reduce COP and/or postural sway to perform the precise visual task (Bonnet and Baudry, 2016a). In our study, the participants were allowed to and needed to rotate their body parts. In such circumstances, it may not have been possible for the CNS to significantly reduce linear body movements on the AP and ML axes in searching vs. free-viewing (Appendix B). Remarkably, these results show that the CNS may not focus – as a main goal – on significantly reducing postural sway to succeed in the search task. Otherwise, postural sway would have been significantly lower in searching than in free-viewing, not higher (Appendix B). Hence, these results contradict the ecological view that postural control should be adjusted alone, independently of eye movements, to succeed in the visual task (Riccio and Soffregen, 1988; Stoffregen et al., 2007). In contrast, as we discussed earlier, our results validate the hypothesis that the CNS may control both eye and body movement in complementary manner, or in synergies (Bonnet and Baudry, 2016b). Remarkably, functional eye–body relations in the search tasks really seem to be crucial for the CNS to succeed in such precise tasks, regardless of the variability of postural sway.

## Limitations and openings

The present study is original, not only because it tested a recent model of postural control, but also because it used a methodology in which the participants were free to look at large and highly complex images. Taken as a whole, the present study showed that healthy young adults used functional negative eye–body synergies in precise search tasks and no such functional correlations in unprecise free-viewing and/or counting tasks. It also showed that even stronger functional negative eye–body synergies could be found in search–counting than in searching only. One main limitation related to the fact that the analyses were exploratory, requiring many statistical tests to be performed. This method was necessary because the significant eye–COP/body relations that we found were not exactly similar to our previous study (Bonnet et al., 2017). A second limitation related to the fact that we did not discuss the significant eye–COP/body correlations found in Table 1 in depth. In fact, we first need to validate the synergistic model (in considering the nature and quantity of positive vs. negative correlations; this was our main goal) before using it to improve our understanding of which visual and postural functions can interact in various visual tasks.

Future studies should be performed with other young adults to test the synergistic model again, to discuss more deeply how eye movements, COP/body movements and cognitive involvement interact with each other and to study the influence of age and pathology (e.g., Parkinson's disease) on the eye–COP/body relations. We initially expect that Parkinson's disease may alter functional eye–COP/body relations in the search task (Bonnet and Baudry, 2016b). In our opinion patients with Parkinson's disease may be less able or even unable to create negative eye–COP/body relations in the search task, in contrast to healthy controls.

## CONFLICT OF INTEREST

None.

## ACKNOWLEDGMENT

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## APPENDIX A. MAXIMUM ROTATIONS OF THE BODY SEGMENTS TO EXPLORE THE IMAGES IN THE FREE-VIEWING AND SEARCH TASKS. THE RESULTS ARE SHOWN IN-SPACE FOR THE HEAD, NECK AND LOWER BACK.

| . | Head-in-space | Neck-in-space | Lower back-in-space |
|---|---|---|---|
| Yaw rotations in the two free-viewing tasks | R: 62.06±5.33°<br>SD: 15.32±1.38°<br>V: 6.02±0.44°.s-1 | R: 26.09±3.74°<br>SD: 6.46±1.07°<br>V: 3.81±0.25°.s-1 | R: 22.79±4.00°<br>SD: 4.83±0.84°<br>V: 3.56±0.49°.s-1 |
| Yaw rotations in the two search tasks | R: 76.63±5.96°<br>SD: 18.44±1.46°<br>V: 7.20±0.48°.s-1 | R: 36.61±3.81°<br>SD: 9.86±1.11°<br>V: 4.51±0.29°.s-1 | R: 38.29±5.63°<br>SD: 9.01±1.23°<br>V: 4.12±0.60°.s-1 |
| Pitch rotations in the two free-viewing tasks | R: 5.68±0.40°<br>SD: 1.24±0.09°<br>V: 3.70±0.22°.s-1 | R: 3.67±0.40°<br>SD: 0.73±0.06°<br>V: 2.94±0.26°.s-1 | R: 3.03±0.28°<br>SD: 0.72±0.08°<br>V: 2.04±0.37°.s-1 |
| Pitch rotations in the two search tasks | R: 7.54±0.56°<br>SD: 1.71±0.13°<br>V: 3.65±0.14°.s-1 | R: 3.99±0.27 °<br>SD: 0.83±0.08°<br>V: 3.08±0.21°.s-1 | R: 3.83±0.33°<br>SD: 0.94±0.10°<br>V: 2.32±0.51°.s-1 |

*Note.* For the markers (head, neck, lower back) displacements, the dependent variables were the range amplitude (R in degrees or °), standard deviation amplitude (SD in °) and mean velocity (V in degrees/seconds or $°.s^{-1}$) in the yaw (left/right) and pitch (up/down) directions.

## APPENDIX B. SIGNIFICANT MAIN EFFECTS OF TASK IN THE REPEATED MEASURE ANOVAS AND ADDITIONAL POST-HOC NEWMAN–KEULS ANALYSES. THE TABLE ONLY SHOWS THE MEAN±SD OF THE THREE TASKS AND THEREFORE DOES NOT SHOW THE EFFECT OF THE COUNTING TASK (COUNTING VS. NO-COUNTING). ONLY THE RESULTS WITH THE RANGE OF ROTATIONS (MAXIMUM ROTATIONS) ARE SHOWN BELOW. THE * SHOWS A SIGNIFICANT DIFFERENCE BETWEEN THE SEARCH AND THE FREE-VIEWING TASKS (POST-HOC NEWMAN–KEULS, *P*<0.01).

| . | Dependent variables | Fixation | Free-viewing | Search | ANOVA |
|---|---|---|---|---|---|
| Linear variables | COP Rap (cm) | 2.15±0.22 | 3.31±0.30 | 3.47±0.25 | $F(2,30)=21.71$, $p<0.01$ |
| | COP Rml (cm) | 1.04±0.09 | 3.88±0.79 | 3.91±0.44 | $F(2,30)=16.21$, $p<0.01$ |
| | Head Rap (cm) | 2.78±0.27 | 4.74±0.46 (*) | 5.51±0.42 (*) | $F(2,30)=42.56$, $p<0.01$ |
| | Head Rml (cm) | 1.10±0.09 | 9.92±0.98 | 11.30±1.00 | $F(2,30)=78.45$, $p<0.01$ |
| | Neck Rap (cm) | 2.51±0.25 | 3.77±0.41 | 4.19±0.39 | $F(2,30)=21.00$, $p<0.01$ |
| | Neck Rml (cm) | 0.96±0.08 | 5.86±0.91 | 7.52±1.04 | $F(2,30)=30.20$, $p<0.01$ |
| | Lower back Rap (cm) | 1.87±0.23 | 3.06±0.43 (*) | 3.86±0.41 (*) | $F(2,30)=23.76$, $p<0.01$ |
| | Lower back Rml (cm) | 0.76±0.09 | 5.12±0.83 (*) | 7.10±1.02 (*) | $F(2,30)=30.90$, $p<0.01$ |
| | Head Ryaw (°) | 7.58±1.09 | 62.06±6.53 (*) | 81.60±8.63 (*) | $F(2,30)=77.39$, $p<0.01$ |

(*continued*)

| | Dependent variables | Fixation | Free-viewing | Search | ANOVA |
|---|---|---|---|---|---|
| Angular variables | Head Rpitch (°) | 1.63 ± 0.14 | 5.68 ± 0.49 (*) | 7.54 ± 0.69 (*) | $F(2,30)$= 57.83, $p$<0.01 |
| | Neck Ryaw (°) | 2.15 ± 0.28 | 26.09 ± 4.58 (*) | 36.61 ± 4.66 (*) | $F(2,30)$= 34.83, $p$<0.01 |
| | Neck Rpitch (°) | 1.72 ± 0.13 | 3.56 ± 0.42 | 3.99 ± 0.33 | $F(2,30)$= 28.81, $p$<0.01 |
| | Lower back Ryaw (°) | 8.74 ± 2.39 | 22.79 ± 4.90 | 38.29 ± 6.89 | $F(2,30)$= 15.23, $p$<0.01 |
| | Lower back Rpitch (°) | 1.25 ± 0.14 | 3.03 ± 0.34 (*) | 3.83 ± 0.41 (*) | $F(2,30)$= 30.63, $p$<0.01 |

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