Original contribution

Effects of gymnastics expertise on the perception of body orientation in the pitch dimension

Lionel Bringoux[a,b], Ludovic Marin[a], Vincent Nougier[a,*], Pierre-Alain Barraud[b] and Christian Raphel[b]
[a]*Laboratoire Sport et Performance Motrice, Université Joseph Fourier, Grenoble, France*
[b]*Unité de Psychologie, Centre de Recherche du Service de Santé des Armées, Grenoble, France*

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The purpose of this study was to investigate how experts in motor skills requiring a fine postural control perceive their body orientation with few gravity based sensory cues. In Experiment 1, expert gymnasts and controls had to detect their body tilt when pitching at a velocity of 0.05 $deg.s^{-1}$, in two conditions of body restriction (strapped and body cast altering the somatosensory cues). Contrary to the experts, the controls exhibited a larger body tilt when totally restrained in the body cast. In Experiment 2, subjects had to estimate their Subjective Postural Vertical (SPV) starting from different angles of pitch tilt. The controls exhibited significant errors of SPV judgement whereas the experts were very precise. These results suggest that 1) somatosensory cues are more informative than otolithic cues for the perception of body orientation, and 2) the efficiency of otolithic and/or interoceptive inputs can be improved through a specific training to compensate for the lack of somatosensory cues.

Keywords: Spatial orientation, perception, human expertise, sensory adaptation

*Correspondence to: Vincent Nougier, Université Joseph Fourier, Laboratoire Sport et Performance Motrice, B.P. 53 F38041, Grenoble cedex 9, France. Tel.: +33 4 76 51 41 95; Fax: +33 4 76 51 44 69; E-mail: vincent.nougier@ujf-grenoble.fr.

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1. Introduction

It is well known that the perceived orientation of the body, based on the integration of sensory information from the visual, somesthetic and vestibular systems, is fundamental to perform a motor task [13]. The implication of the otolith organs as precise graviceptors [25, 28] has been often evoked in the perception of the head position and to an extent in the perception of the body orientation in space. Indeed, as they are sensitive to linear accelerations, they are sensitive to gravity and should then provide accurate information about the position of the head with respect to the direction of gravity in absence of inertial force [1]. From an electrophysiological point of view, slight modifications of head position lead actually to variations of the afferent signal at the vestibular nerve ending [8]. However, several studies moderate the role of the otolith organs in the perception of postural orientation. For example, in water immersion, when visual and somatosensory (tactile and prioceptive) systems have a limited access to gravity cues, subjects make great errors in body orientation [16, 22,26]. Moreover, it has been shown that labyrinthine defective subjects obtain performances similar to those observed for normal subjects in judgement precision of their subjective postural vertical [3,4]. Finally, it was recently demonstrated that the threshold for the detection of a slow body tilt in darkness was much higher for normal subjects when somatosensory information was altered [27], showing the importance of proprioceptive as well as touch and pressure cues for human spatial orientation [12,14].

However, it is unclear whether this somesthetic prevalence for the perception of body orientation without vision still exists for subjects that are trained to face high postural constraints. Indeed, it remains to investigate how the expertise in tasks requiring a fine control of body position (e.g., gymnastics) can enhance the perception of body orientation in environments with few gravity based sensory cues (particularly when somatosensory information about gravity is altered).

Although few studies focused on the perceived orientation of the body by expert athletes, we know that sport practice can enhance the use of some parts of the perceptual system. For example, it has been reported [11] that experts in "open skill" sports (e.g., basketball, volleyball and water polo) use their visual system better than novices (see also Paull and Glencross [24] for baseball). For other sports, like Tai Chi Chuan, the somatosensory perception seems to improve with the athletes' level of expertise [10].

The goal of the present experiments was to determine whether experts in motor skills requiring a fine control of body orientation (such as gymnasts, divers, synchronized swimmers, etc.), may modify the perceptual process leading to judgements of orientation, that is (1) whether these experts are able to judge their body orientation more accurately than control subjects in poor sensory environments (without visual cues and semicircular canals stimulation), and (2) whether they are able to maintain a good perception of their body orientation, independently of the available sensory inputs (i.e., with or without gravity based somatosensory cues). These two experiments will allow us to determine the predominance of otholithic and/or somatosensory system for perceiving body orientation.

2. General methods

The two experiments were carried out with subjects' signed informed consent in compliance with the Huriet Law (i.e., Helsinki Convention) which governs and regulates human experimentation in France. The common "suppression sensorial paradigm" was used to create a poor sensory environment, and to investigate whether participants are mainly dependent on one type of sensory information [6,23,27]. In order to eliminate visual and semicircular canals information, subjects were placed in complete darkness, and were passively displaced on a motorized platform (Fig. 1) allowing backward and forward rotations in the sagittal plane at a constant velocity of 0.05 deg.s^{-1}, following an initial acceleration phase at 0.005 deg.s^{-2}. Moving the platform at this very slow velocity prevented a stimulation of subjects' semicircular canals [2,6,28]. Position signals from the platform were sampled at 20 Hz (12 bit A/D converter).

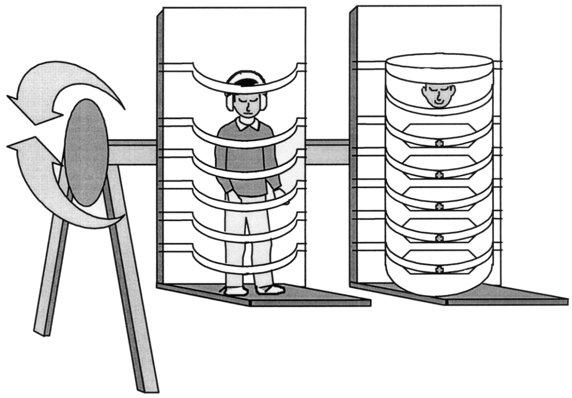


Fig. 1. Illustration of the experimental set-up for the strapped and body cast conditions.

In order to focus onto the somatosensory and otolithic implications, two conditions of body restriction were used in each experiment. In the so-called strapped condition (see Fig. 1), subjects were attached onto the platform by means of six large straps fixed at the level of the head, breast, abdomen, hips, knees and ankles. In such a design, somatosensory information was available. In the body cast condition, subjects were completely immobilized in a specific device looking like a body cast in which the use of the gravity based somatosensory information was almost suppressed. This body cast was composed of three plastic envelopes full of micro-marbles and connected to a depressurization device. The surface of the plastic envelopes was very thin in order to ensure the closest contact as possible with subjects' body. The wrapping was done in the supine posture with no contact of the soles with the foot-rest. The back envelope was directly attached onto the platform and partially recovered the subjects' body. The front envelope was put onto the subjects' body and was immobilized by means of the straps. The third envelope specifically immobilized the head and shoulders. When the subjects were appropriately wrapped in the body cast, the depressurization was realized. In the body cast condition, the body pressure was distributed against all parts of the body, including the head. Thus, the specific pattern of tactile information about body position such as the gluteal or plantar support surface was no longer available.

3. Experiment 1

The purpose of Experiment 1 was to study, for experts in motor skills requiring a fine body orientation and control subjects, the threshold for the perception of a body tilt when subjects started from an initial vertical body orientation. More specifically, we investigated the respective contribution of somatosensory and otolithic cues, when immobilizing the subjects in different conditions of body restriction (strapped and body cast conditions).

3.1. Methods

3.1.1. Subjects

Two groups of athletes voluntarily participated in the experiment as unpaid subjects. 5 expert gymnasts (4 males and 1 female, aged 18 to 22 years, high 165 to 175 cm) composed the expert group. All these gymnasts had more than 10 years of experience in gymnastic competitions at a regional or higher level. 5 non-gymnast subjects (3 males and 2 females, aged 19 to 22 years, high164 to 181 cm) composed the control group. All members of this group had more than 10 years of experience at a regional or higher level in sports which do not require a high demand in the control of spatial orientation (volleyball, handball, running athletics or tennis), so that they could be also considered as sport experts.

3.1.2. Task and procedure

Eyes closed in the complete darkness, subjects' task was to perceive very slow backward and forward body tilts when starting from a vertical position in both conditions of body restriction (see general methods). Prior to each trial, subjects closed their eyes and were oriented in the initial vertical position. When ready, the trial was initiated and it ended with the detection of a body tilt. It has been emphasized elsewhere [6,27] that the detection of a change in body orientation can occur before the direction of the tilt can be reported. Subjects were instructed to indicate verbally when they perceived a body tilt and in which direction. In order to obtain responses that exceeded that of simple chance, subjects were also instructed to give their level of confidence on a five-point scale. They were encouraged to postpone their response until reaching the level 4 on the five-point scale (4.2 in average). Following their response, subjects were allowed to open the eyes and the platform was brought back to the starting position. The two conditions of body restriction were tested in separate blocks of trials. For each condition, two trials for each direction of tilt (backward and forward) and one catch trial with the platform remaining immobile were executed randomly for a total of 10 trials. The catch trials were used to further ensure that subjects did not detect movements of the platform by guessing. The duration of the catch trials varied randomly from 120 to 300 s by steps of 60 s. The blocks of trials were presented randomly on two separate days. Each experimental session lasted approximately one hour. The percentage of errors (perceiving a wrong direction of platform rotation or no displacement) was of 3,8% and 90% of these errors were during the first trial. Subjects who made errors reported a posteriori that they were stressed at the beginning of the session. When making an error, subjects were given a repeat of that trial at the end of the block.

3.2. Results and discussion

A 2 groups (experts vs. controls) $\times$ 2 conditions of body restriction (strapped vs. body cast) analysis of variance (ANOVA) with repeated measures on the last factor was applied to the threshold for body tilt. Whenever necessary, post-hoc Newman-Keuls or simple effects tests were used to examine the significant interactions.

Results showed a main effect of Group $(F(1,8) = 227.17, p < 0.01)$. The experts perceived a modification of their body orientation faster than the controls (1.97 vs. 11.67 deg). Results also showed a main effect of body restriction $(F(1,8) = 136.88,\ p < 0.01)$. Subjects detected a change in body orientation faster in the strapped than in the body cast condition (4.39 vs. 9.25 deg). The interaction of group $\times$ condition of body restriction (Fig. 2) was also significant $(F(1,8) = 36.09,\ p < 0.01)$. The decomposition of the interaction into its simple main effects showed that the threshold for the perception of a body tilt was higher in the body cast than in the strapped condition for the controls ($p < 0.01$), whereas there was no effect of body restriction for the experts ($p > 0.05$).

The purpose of the present experiment was to determine whether experts are able to detect a body tilt faster than control subjects, and whether these two groups primarily perceive the change of body orientation trough the somatosensory or vestibular system in order to compensate for the lack of relevant visual information. Results showed that threshold for the perception of a body tilt was lower when controls were partially restrained than when they were completely immobilized in the body cast. Interestingly, the control group showed performances similar to those reported by non expert subjects in other studies [27]. Moreover, it is worth noting that the absence of tactile and proprioceptive gravity

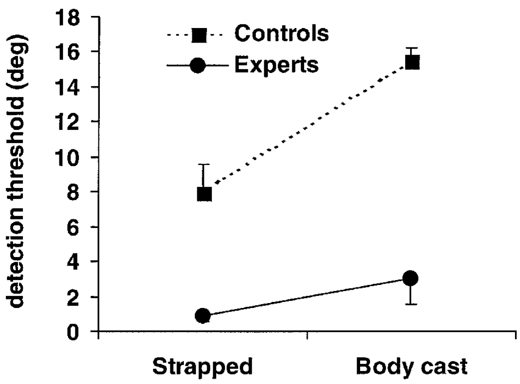


Fig. 2. Mean angular threshold for the perception of a body tilt and standard deviation for the experts and the control group and for the two conditions of body restriction.

cues induced by the body cast had no effect for the experts. These results suggested that the experts were less dependent than the controls on the availability of gravity based somatosensory information. They also led to the conclusion that the experts were more efficient than the controls in using other sensory information such as otolithic cues, inertia of the mass of the viscera and/or homeostatic blood pressure for perceiving body orientation in space. This suggested that the practice of gymnastics could enhance the functional characteristics of some sensory systems involved in the perception of body orientation.

4. Experiment 2

The purpose of Experiment 2 was to investigate whether experts were more efficient than controls in judging their Subjective Postural Vertical (SPV), and whether subjects were more efficient in indicating their SPV than in detecting a change in body orientation. Subjects were asked to estimate when they reached a vertical position, starting from various tilted positions [3,4].

4.1. Methods

4.1.1. Subjects

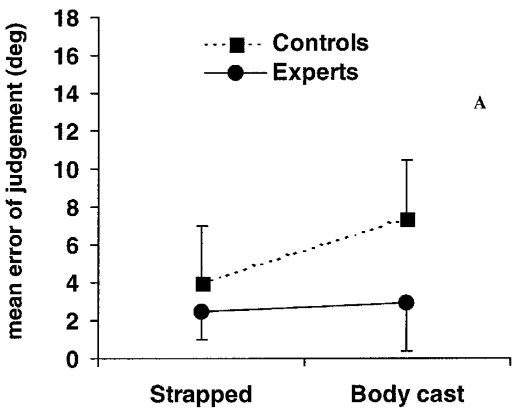
Two new groups of athletes voluntarily participated in the experiment as unpaid subjects. 6 expert gymnasts (4 males and 2 females, aged 19 to 23 years, high 164 to 180 cm) composed the expert group. All these gymnasts had more than 10 years of experience in gymnastic competitions at a regional or higher level. 7 non-gymnast subjects (4 males and 3 females, aged 19 to 25 years, high 163 to 184 cm) composed the control group. All members of this group had more than 10 years of experience at a regional or higher level in sports which do not require a high demand in the control of spatial orientation (volleyball, handball, running athletics or tennis), so that they could be also considered as sport experts.

4.1.2. Task and procedure

The apparatus was the same as in Experiment 1. Subjects' task was to verbally indicate in total darkness when they reached the vertical in the pitch dimension. The two conditions of body restriction were investigated in two counterbalanced sessions. Each session was composed of 6 trials crossing randomly 2 directions of initial orientation (forward and backward) $\times$ 3 angles of initial orientation (10, 20 and 30 deg). Subjects were first tilted to the desired initial orientation at a constant velocity of 4 deg.s^{-1} (with an initial acceleration and final deceleration of 2 deg.s^{-2}). After 15 seconds allowing the information issued from the semicircular canals to be close to zero [8,9], the tilting platform started its slow displacement (0.05 deg.s^{-1}) back to the direction of the gravitational vertical. Subjects had to indicate when they felt that the vertical was reached. At the end of each trial, subjects were replaced in the upright position and the room was illuminated for 20 seconds in order to avoid any postural aftereffect or disorientation illusion prior to the next trial. Subjects were neither instructed about the direction and magnitude of the initial orientation, nor about the angular velocities of platform rotation. For making their judgement, subjects were strongly encouraged to use available body sensations rather than doing inferences about the time they spent during one trial.

4.2. Results and discussion

The mean absolute error of judgement was used to analyze subjects' errors with respect to the gravitational vertical, independently of the signed direction of the body tilt [3,4]. A 2 groups (experts vs. controls) $\times$ 2 conditions of body restriction (strapped vs. body cast) $\times$ 2 directions of initial tilt (forward vs. backward) $\times$ 3 angles of initial tilt (10, 20, and 30 deg) ANOVA with repeated measures on the last three factors was applied to the data. Results showed that the experts made smaller errors than the controls (2.7 deg $\pm$ 2.06 vs. 5.68 ± 4.53, $F(1, 11) = 9.31$, $p < 0.01$). They also showed that the mean error of judgement was smaller for the strapped than for the body cast



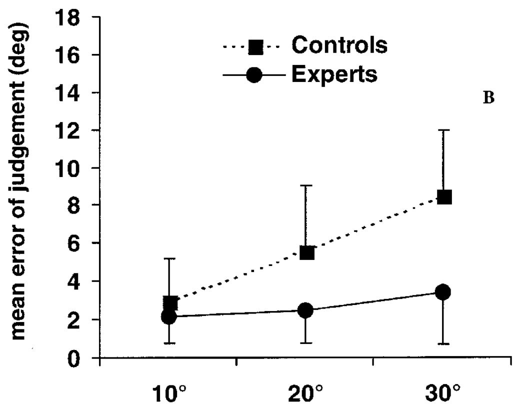


Fig. 3. Mean SPV judgements and standard deviation for the experts and the control group, A) for the two conditions of body restriction and B) for the three angles of initial body tilt.

condition (3.29 deg $\pm$ 2.53 vs. 5.32 deg $\pm$ 4.69, $F(1,11) = 17.01$, $p < 0.001$). There was also a main effect of the angle of initial tilt, ($F(2,22) = 29.16$, $p < 0.001$), but no effect of the direction of this initial tilt. A post hoc analysis (Scheffé test) showed that the error of judgement increased from 10 to 30 deg (2.6 deg $\pm$ 1.9, 4.16 deg $\pm$ 3.18 and 6.15 deg $\pm$ 5.09, for the 10, 20 and 30 deg tilted positions, respectively, $ps < 0.05$). Finally, there were also significant interactions of group $\times$ body restriction ($F(1,11) = 10.15$, $p < 0.01$), group $\times$ angle of initial tilt ($F(2,22) = 11.98$, $p < 0.001$), and body restriction $\times$ angle of initial tilt ($F(2,22) = 5.74$, $p < 0.01$). The decomposition of the first interaction showed that there was no effect of body restriction for the experts ($p > 0.05$), whereas the mean error of judgement was higher in the body cast than in the strapped condition for the controls ($p < 0.001$, Fig. 3(A)). The decomposition of the second interaction showed that there was no effect of the angle of initial tilt for the experts

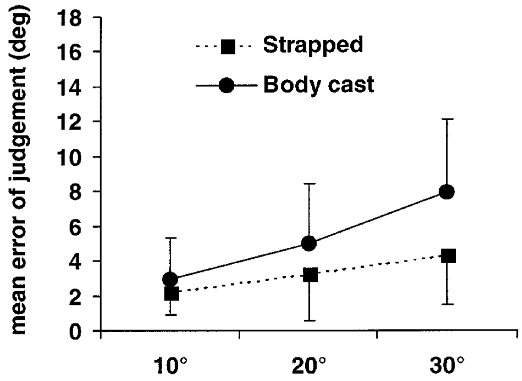


Fig. 4. Mean SPV judgements and standard deviation for the two conditions of body restriction and for the three angles of initial body tilt.

($ps > 0.05$), whereas the mean error of judgement increased with the angle of initial tilt for the controls ($ps < 0.001$, Fig. 3(B)). Finally, the last interaction showed that the effect of the angle of tilt was greater in the body cast than in the strapped condition (Fig. 4).

Regarding the data obtained for the controls, the greater the body restriction was, the larger the error of judgement was with respect to the absolute vertical implying a higher deviation of SPV on the side of the initial tilt. In other words, a greater alteration of the somatosensory cues induced a more pronounced shift in the direction of the initial tilt. It is well known that both normal and labyrinthine defective subjects are able to give fairly accurate estimates of the SPV [3,5]. The present results clearly suggested that the somesthetic system plays a major role in estimating the direction of SPV [4].

Results also showed that the greater the initial angle of tilt, the greater the error of judgement was for the controls with respect to the gravitational vertical. Because of the very slow rotation of the platform, changes in the sensory cues within that time were very low, resulting in an underestimation of the current body tilt. This suggested that, in absence of enough dynamic information about body orientation with respect to their own internal reference of verticality [15,18], the controls tend to perceive the current body position as nearer to the upright reference position than it actually is. As previously indicated, this underestimation increased in the body cast condition for the control group.

Interestingly, the expert gymnasts proved to be more precise than the controls in determining their SPV. In addition to a lower dependence on the somatosensory cues, this behavior could result from a more efficient comparison process between reduced or non-dynamical gravitational cues and internal estimates of body verticality [15,18]. The absence of effect of body restriction and initial tilt for the experts strongly suggests that the perception of body orientation can be improved through intensive learning.

5. General discussion

5.1. Sensory implications and expertise

Results of the present experiments showed that the perception of body orientation was less precise when the controls were completely immobilized in the body cast than when they were partially restrained. In the body cast condition, the appropriate use of tactile and proprioceptive information was altered. These results confirmed that, at very slow velocities, the otolithic organs are poor graviceptors for normal subjects [27]. In the strapped condition, results suggested that proprioceptive and tactile sensory signals provided enough information about body orientation with respect to gravity and that other sensory signals contributed slightly to the perception of body orientation. In the body cast condition, however, the role of pressure and shear receptors of the skin was limited too. There was no contact of the soles with the foot-rest and the body cast produced an almost constant pressure on the whole body. This kind of information appears to be of great importance for the control subjects, who tend to primarily use somatosensory cues to perceive their body orientation.

Contrasting with the controls, the experts were not disturbed by the absence of gravity based somatosensory information. Several explanations may be proposed to explain this result. The first one is based on a peripheral adaptation of the sensory receptors still available to convey cues about body orientation with respect to gravity. Among them, the otolith inputs, as well as interoceptive signals such as the inertia of the mass of the blood in the large vessels and of the mass of the viscera [7,19–21] could play an increasing role in the perception of body orientation for the experts. According to this first hypothesis, the threshold for the sensitivity to a stimulus variation (e.g., the direction of shearing forces) might be lowered at the level of these sensors through a specific training such as gymnasts do. However, it is known that very slight modifications of head position lead actually to variations of the afferent signal at the vestibular nerve ending [8]. This suggests that the sensory adaptations rather occur at the level of the Central Nervous System (CNS) implying a modification of signal to noise ratios. Slight modifications of otolithic and/or interoceptive signals would then be more informative for the experts than for the controls.

Another way of explanation focuses on the integration process of the available gravity based sensory information. Gymnasts, as probably every experts in motor skills requiring a fine control of body orientation, are trained to face high postural constraints in some particular environments in which the sensory redundancy is often limited (e.g., disrupted somatosensory or visual inputs). Thus, it is likely that these subjects have unconsciously learned perceptual strategies that consist of picking up the relevant information still available. During the integration process, the experts would be more efficient for extracting and associating significant and relevant cues about their orientation in space from the sensory systems that are still potentially informative.

5.2. Internal reference and expertise

Another result may explain how expertise can lead to a better perception of body orientation. Regarding Experiment 2, the error of judgement increased with the angle of tilt for the controls, whereas it remained smaller and almost constant for the experts. In a task involving SPV judgements, subjects had to indicate as precisely as possible when they reached the vertical, that is, to associate a specific multisensory configuration to a particular postural orientation. Previous authors proposed that the CNS incorporates information about body dynamics and sensory cues to develop an internal model [17,18]. The output of this internal model, that is, expected sensory afferences for a particular body position, is compared to the actual available sensory afferences. The error between this internal model and the actual sensory afferences would be used to drive the central estimate towards the value of reference.

However, in absence of enough dynamic information about body orientation with respect to their own reference of verticality [15], the control subjects tended to perceive their current body position as nearer to the upright reference position than it was really. This phenomenon increased as the initial angle of tilt was greater. The absence of such a perceptual bias for the experts could result from a more efficient comparison process between reduced or non-dynamical gravity based cues and internal estimates of body verticality [15,18]. Furthermore, it can be postulated that intensive training develops a more complete and precise internal model of verticality. Indeed, for the experts, such an internal model may be based on an expected multisensory configuration including every sensory cues that are able to convey an information about body orientation with respect to gravity.

In conclusion, the most striking result of the present experiments was that, in an environment with few gravity based sensory cues, the perception of body orientation was more efficient for experts in motor skills requiring a fine postural control than for control subjects. For the control subjects, somatosensory cues seem to be more informative than otolithic cues for the perception of body orientation without visual and semicircular canals information. However, the relevance of otolithic and/or interoceptive inputs seems to increase with increasing expertise. This finally suggests that the efficiency of the integration process leading to the perception of the body orientation in space can be significantly improved through a specific training such as the gymnasts do.

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