Distinctive brain functional correlates of passive driving in naïve and professional race-car drivers: a fMRI study

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Abstract (250 words)

Driving is a complex behavior that requires the integration of attentional, perceptual, motor and other cognitive functions. While many studies have investigated brain activity related to driving simulation in a wide gamut of conditions, little is known about the brain functional correlates of professional competitive driving, which requires greater motor and attentional skills. Ten professional race-car drivers and nine healthy 'naïve' volunteers underwent brain scan examinations by functional magnetic resonance imaging (fMRI) while presented with short movies depicting a Formula One car racing on different official circuits. We adopted analysis approaches based on brain response similarity across different subjects (i.e., Inter-Subject Correlation, ISC) to investigate functional correlates of driving in the two samples. In addition, a functional connectivity analysis was used to explore and compare task-related networks. Results showed that professional drivers are characterized by a stronger recruitment of prefrontal and motor control devoted areas as compared to non-experienced drivers. On the other hand, naïve drivers have a more robust response in brain regions involved in visual information processing. These findings indicate that the brain functional organization developed by skilled race-car drivers differs from that in subjects with an ordinary driving experience. In fact, while naïve drivers possess only a basic driving knowledge, professional drivers have been trained specifically in car racing and have the motor competence to effectively cope with the specific situations arising during the Formula One passive driving task. Differently put, naïve individuals simply *watched* the race, while professional drivers *acted* the race.

1. Introduction

The study of the brain functional correlates associated with expertise acquisition in selected highly skilled populations, such as musicians or elite athletes, has received a steadily growing attention over the last few years [1-4]. As a matter of fact, these particular individuals undergo intensive training programs that have been correlated with a number of brain functional and structural plastic adaptations eventually subserving their exceptional abilities in specific fields [1, 3-6]. For instance, studies in so called '*elite athletes*', such as archers [7-10] or divers [11, 12], suggested that these subjects may be characterized by different brain functional correlates with respect to 'common' individuals [1, 2]. Similarly, we recently demonstrated that during visuo-spatial and motor processing, Formula racing car drivers present a distinctive functional organization as compared to untrained naïve drivers [13, 14]. While a greater brain operative efficiency in these particular functions could be clearly relevant in supporting a high level driving performance, it is still unknown whether exceptional car racing abilities are associated with the acquisition of task-specific functional substrates.

The present study was designed to determine whether elite and naïve drivers are characterized by distinct brain functional correlates during passive race-car driving. To this aim, we used functional magnetic resonance imaging (fMRI) to evaluate patterns of brain response and regional interaction during a passive driving task in which subjects watched, from the driver's perspective, a Formula One car running on four different circuits. A passive task, rather than an active one, was selected for two main reasons: (i) to avoid possible confounds related to the different ability level of the two groups [15], and (ii) to avoid any potential artifacts caused by movements during the fMRI scanning [16]. Experimental paradigms based on motor imagery or passive observation of video-clips have been extensively adopted in studying complex human behaviors, including road-car driving [17-19], in order to overcome limitations related to their reproducibility in a laboratory setting [16]. Indeed, it has been established that both approaches can evoke a brain response that largely overlaps with the one observed during the actual execution of the same activities [20-22], and that this functional representation is dependent on the level of expertise achieved by the observer [23, 24]. In particular, passive driving has been associated with the recruitment of a distributed functional network, including striate and extrastriate cortex, superior and inferior parietal lobules, prefrontal cortex and sensorimotor areas, which is quite similar, although not identical, to the one observed during simulated 'active' driving [17, 19, 25-28]. Interestingly, while a growing number of studies recently started to explore the brain functional correlates of driving behavior in general [17-19, 25-31], none has yet investigated whether long term practice in high speed car racing is associated with any rearrangement of the brain functional architecture.

We hypothesized that although professional and naïve car drivers may share a similar general expertise in driving 'normal' road-cars, their brain activity would be substantially different during a Formula One passive driving task due to the differences in their specific sport-related expertise. In particular, we expected professional drivers, who achieved a greater expertise in driving fast race-car through intensive trainings and competitions, to show a more 'effective' motor representation, as expressed by a more robust and 'integrated' recruitment of brain areas involved in motor planning and control.

2. Subjects and Methods

2.1. Subjects.

Ten professional (mean age ± S.D.= 24 ± 5 years) and 9 naïve (28 ± 4 years; p= ns) car drivers were studied. Professional car drivers were recruited from the pool assisted by the Formula Medicine® group (Viareggio, Italy). All car racers were actively participating in a professional racing tournament (as Formula One Championship, World Series, Formula 3, etc.) and had a minimum of 4 year expertise in amateur and professional racing. Naïve car drivers were recruited from the general population. All subjects were right-handed healthy males, with no history of any relevant medical, neurological or psychiatric disorder. Clinical examinations and laboratory testing, including a structural brain MRI scan exam, were performed to rule out history or presence of any disorder that could affect brain function and development. All subjects were free of medications. All volunteers gave their written informed consent after the study procedures and risks involved had been explained. The study was conducted under a protocol approved by the Ethical Committee at the University of Pisa Medical School (Protocol n. 020850). All participants retained the right to withdraw from the study at any moment.

2.2. Image Acquisition.

Functional data were acquired on a GE Signa 1.5 Tesla scanner (General Electric, Milwaukee, WI) using the following parameters: repetition time = 2500 ms, number of axial-slices = 21, slice thickness = 5 mm, field of view = 240 mm, echo time = 40 ms, flip angle = 90°, image plane resolution = 128 x 128. While in the magnetic resonance scanner, participants were presented with four color video-clips recorded by an on-board camera placed on a Formula One car running on different circuits: Spa-Francorchamps (Spa, Belgium), Magny-Cours Circuit (Nevers, France), Autodromo Enzo e Dino Ferrari (Imola, Italy) and Bahrain International Circuit (Sakhir, Bahrain). Visual stimuli were presented on a rear projection screen viewed through a mirror (visual field: 25° wide and 20° high). All four video-clips were presented in a single continuous sequence (with a 1 second black screen separating each clip from the following) overall lasting 340 seconds (136 volumes). A black screen was showed at the beginning of each functional time series for 15 seconds (6 volumes) that were subsequently discarded to allow for magnetic field stabilization. To maximize compliance and attention to the stimuli, before the fMRI scanning subjects were instructed to imagine themselves driving the racing car. For each subject we also obtained a high-resolution T_1-weighted spoiled gradient recall image (slice thickness = 1 mm, echo time = 3,8 ms, repetition time = 20 ms, flip angle = 15°, field of view = 220 mm) to provide detailed brain anatomy for functional data localization.

2.3. Functional Data Preprocessing.

We used AFNI and SUMA software packages to analyse and display functional imaging data (http://afni.nimh.nih.gov/afni; [32]). All obtained functional volumes were coregistered (*3dvolreg*), temporally aligned (*3dTshift*), and spatially smoothed using a Gaussian kernel of FWHM 8mm (*3dmerge*). Individual run data were scaled by calculating the mean intensity value for each voxel during the entire functional run, and by dividing the value within each voxel by this averaged baseline to estimate the percent signal change at each time point. Additional preprocessing steps included removal of other effects of no interest, specifically, head motion and drifting effects, from all timeseries. Individual preprocessed functional data were registered to the Talairach and Tournoux Atlas coordinate system [33], and resampled into 2 mm^3 voxels. Brain activations were anatomically localized on the naive and professional group-averaged Talairach-transformed T_1-weighted images, and visualized on normalized SUMA surface templates.

2.4. Inter-Subject Correlation Analysis.

The exploration of brain functional responses during a natural viewing condition is not easily attainable using classical analysis approaches based on general linear model (GLM) [16]. Thus, to determine the brain functional response during continuous passive driving, we used an Inter-Subject Correlation (ISC) analysis [34]. The ISC approach is based on the assumption that some events included in naturalistic stimuli are able to evoke functionally selective, time-locked, brain response with high reproducibility across different subjects, and thus operates in a completely data-driven fashion [35].

Pearson's coefficient was used to determine correlation between every pair of subjects within each group on a voxel by voxel basis. Thus, as we included 10 professional and 9 naive drivers, we obtained a total of 45 and 36 correlation maps respectively, that were then used to calculate the averaged correlation coefficient per voxel in each group. To define significant correlations in obtained group maps we performed a fully non-parametric voxel-wise permutation test using ISC-toolbox [36]. This program generated the permutation distribution by circularly shifting each subject's time series by random amount so that they were no longer aligned, and then calculated the new correlation values. The full permutation distribution has been approximated with 100,000,000 realizations for each group. Correction for multiple comparisons was attained using false discovery rate (FDR) with independence or positive dependence assumption [36-38]. The significance threshold was set at FDR corrected $p < 0.001$.

To better characterize and visualize ISC differences between professional and naïve drivers, we computed a contrast between mean correlation maps of the two groups and compared real results with those obtained when all voxels timeseries were no longer aligned in time. To do this, we first applied Fisher’s z transformation to correlation coefficients obtained for each pair of subject to improve their normality (although for relatively small r values, such as those obtained in this study z transformation lead to minimal value changes).

Then, we computed average correlation coefficient per voxel and per group, and calculated the simple mathematical difference between common voxels (logical AND) of the two group correlation maps ('professional – naïve'). To determine which of the contrast values were higher than can be expected by chance, we generated a new 'dummy' contrast dataset applying the procedure described above after shifting the timecourses of each subject and voxel by a random amount. The distribution of all correlation values, including those from 'real' results and those obtained in the 'dummy' contrast map, were used to determine the cut-off that produced a false alarm probability of $p < 0.005$ (e.g., [39]).

2.5. Functional Connectivity Analysis.

In order to reduce the probability of identifying spurious correlations, the timeseries extracted from a single voxel located in lateral ventricles, the six motion correction parameters derived from the volume registration and the polynomial regressors accounting for baseline shifts and linear/quadratic/cubic drifts were mathematically removed from the preprocessed (as defined in 2.3) voxel timecourse (*3dSynthesize*) [40]. In addition, timeseries were low-pass filtered (*3dFourier*) at 0.15 Hz to remove high frequency physiological artifacts including cardiac and espiratory pulsatility [41, 42].

We divided each brain hemisphere into 45 cortical and subcortical regions using the Eickhoff-Zilles Atlas [43]. Regional mean timeseries were estimated for each individual by averaging the fMRI timecourses over all voxels in each of the 90 regions. For each subject an individual correlation matrix was obtained by computing the Pearson's correlation coefficient between each region of interest and all other considered regions of the brain. In order to determine significantly different correlations between the two examined groups, we converted correlation coefficients of each subject into z scores using Fisher's z transformation and then performed an unpaired t-tests at each location of the correlation matrix ($p < 0.05$).

3. Results

3.1. Inter-Subject Correlation Analysis.

In both professional and naïve drivers passive driving significantly modulated regional activity in a set of cortical areas known to be involved in visual information processing, vigilance, attention, motor control, and more specifically, in driving behavior [17, 25]. In fact, both groups showed a significant brain response in bilateral visual cortex (BA17, BA18, BA19), precuneus, cingulate cortex, parahippocampus, superior parietal lobule, medial frontal gyrus (BA6), right dorsolateral prefrontal cortex (BA9) and left precentral gyrus (Fig. 1). However, professional drivers showed additional significant correlations in bilateral inferior parietal lobule, inferior/middle temporal cortex, medial/superior frontal gyrus, inferior frontal gyrus, left middle frontal gyrus, and right precentral gyrus.

These observation were confirmed by the contrast carried out between the two groups ($p < 0.005$), which revealed a significantly stronger correlation in professional drivers, as compared to naïve drivers, in bilateral precuneus, inferior parietal lobule, precentral gyrus, middle temporal gyrus, parahippocampal gyrus, middle frontal gyrus, right inferior frontal gyrus, medial frontal cortex, and posterior cingulate cortex. On the other hand, naïve drivers showed stronger correlations in bilateral cuneus and lingual gyrus, left middle occipital cortex and left superior parietal lobule.

[Insert Figure 1 about here]

3.2. Functional Connectivity Analysis.

Individual functional connectivity matrices obtained with an explorative approach were used to calculate averaged group maps (Fig. 2a) and to compute a comparison between professional and naïve drivers (Fig. 2b) via unpaired t-test ($p < 0.05$). Results showed a number of reinforced correlations in professional as compared to naïve drivers, mostly involving prefrontal cortex, anterior and posterior cingulate cortex and basal ganglia. In particular, areas that showed the greatest changes in inter-regional correlations included medial and orbitofrontal cortex, superior frontal cortex, cingulate cortex, motor and premotor areas. On the other hand, naïve drivers showed fewer stronger correlations, mostly between areas belonging to striate and extrastriate visual areas and parietal cortex (Fig. 2).

[Insert Figure 2 about here]

4. Discussion

The present work was designed to assess whether differences in skills and expertise in a complex behavior, such as driving of a racing car, are associated with distinctive brain functional correlates. Specifically, we used fMRI to evaluate brain response in professional race-car drivers and untrained naïve drivers during a continuous passive Formula One driving task. We adopted a passive task, rather than an active one, both to avoid potential artifacts caused by movements while in the scanner, and to avoid any confounding factors linked to the different skills level of the two groups [44]. Previous works have demonstrated that brain response during passive observation of specific activities, such as dancing or driving, is similar to the one exhibited during actual execution of the same acts [20, 24, 45, 46]. Moreover, a number of studies indicated that this functional motor representation is truly effective only if the observer has achieved a certain degree of direct expertise in the specific activity [23, 24]. Therefore, we hypothesized that although driving a common road-car in the traffic and driving a race-car on a circuit may tap on similar brain functions, the specific skills developed by professional drivers would be associated with a more efficient motor representation, as expressed by a distinctive activation pattern and a reorganization of the underlying functional network.

4.1. Distinctive brain response modulation during passive driving in expert and naïve drivers

As expected, in both professional and naïve drivers, passive driving was associated with the recruitment of a widespread cortical network already described in previous investigations of the functional correlates of driving [17, 25-27, 29]. This network included bilateral areas devoted to visual processing (striate and extrastriate cortex), superior and inferior parietal cortex, right dorsolateral prefrontal cortex and left sensorimotor cortex. However, as predicted, professional and naïve drivers showed a substantially different pattern of brain activity. In fact, while untrained subjects showed a consistent modulation of brain response mostly limited to visual brain areas (i.e., cuneus, lingual gyrus, middle occipital gyrus), professional drivers were characterized by a stronger response in a number of additional cortical regions, including bilateral cingulate cortex, parahippocampus, precuneus/superior parietal lobule, motor/premotor cortex, dorsolateral prefrontal cortex, and middle temporal cortex. Most of these areas have been previously put in relation with different aspects of driving behavior, including vigilance, visuo-spatial monitoring, action preparation and motor control [25, 26].

Moreover, an exploratory connectivity analysis was used to characterize functional networks recruited by professional and naïve drivers during the passive driving task. The results revealed significant differences in task-related networks between the two experimental groups. In fact, professional drivers showed higher correlation measures, as compared to naïve drivers, in a number of brain regions, including prefrontal areas, anterior and posterior cingulate cortex and basal ganglia. In particular, some regions were characterized by a high degree of functional reorganization, including orbitofrontal cortex, dorsomedial prefrontal cortex, superior prefrontal cortex, motor and premotor areas. On the other hand, naïve drivers were characterized by higher correlation measures in regions devoted to visual and spatial information processing. These findings are consistent with and reinforce the results obtained using the ISC analysis, indicating a stronger functional coupling between cortical areas involved in motor planning (e.g., premotor cortex, basal ganglia [25, 47]), motor control (e.g., basal ganglia, primary motor cortex [47]) and decision making (e.g., cingulate cortex, orbitofrontal cortex [48, 49]), in professional drivers. In particular, described results show that these brain regions were actually exchanging information and working together at a higher degree during the passive driving task in race-car drivers as compared to naïve individuals.

Overall, described results are consistent with previous findings indicating that during passive observation tasks brain response is strongly dependent on the expertise of the observer in depicted activities [9, 20, 24]. For instance, a stronger response in a number of brain areas, including regions regarded as part of the human mirror neuron system (i.e., premotor cortex and inferior parietal cortex), and regions involved in theory of mind or episodic recall, has been shown in expert archers as compared to untrained individuals, while they observed short movies depicting movements that only the first group was trained to perform [9]. Similar findings have been described using motor imagery paradigms, for example in skilled divers required to imagine movements specifically related to their sport activity [11]. In line with these works, our results indicate that a specific motor expertise is indispensable to obtain an actual motor representation, and not simply a purely visual motor representation [24].

As a matter of fact, although both professional and naïve drivers may know how to drive a common road-car, driving a race-car implies a number of additional skills, from the use of different controls to the management of braking and rapid accelerations. Indeed, the lack of a direct experience in driving race-cars probably prevented the control group from attaining an actual motor representation, relegating the brain functional response to visual areas. In other words, naïve individuals simply watched the race, while professional drivers imagined to race.

4.2. Limitations of the study

While the number of subjects included in the present work may appear to be relatively limited in light of the current standards for fMRI experiments [50], it should be kept in mind the exceptionality of the athletes sample, as the number of professional racing car drivers with experience in Formula One, or other top level championships, is very limited to begin with, and comprises individuals who spend most of their time away, so that the recruitment of individuals who agree to travel to a research center to undergo testing is quite challenging. Furthermore, we posed quite restrictive inclusion criteria, so that subjects with any history of head trauma or accident or any other relevant medical condition would not be eligible for the study. It should be also emphasized that the consistency of results obtained using different analysis approaches, and the agreement with findings described by previous studies, support the reliability of described functional differences, despite the relatively limited number of participants.

The use of a passive task may be considered as a potential limit for the present study, as one can object that observed differences between the two groups could simply reflect differences in levels of attention and/or emotional participation. While we do not have a valid measure of effort and attention levels or emotional response in our samples, the brain functional results indicate that this is unlikely to be the case. Both groups paid a great attention during the passive driving task, as shown by the strong activation in the visual cortical areas, that is known to be modulated by attention to the task [51].

An additional potential confounding factor is represented by the fact that the driving video-clips were recorded on four Formula One official circuits, that were relatively familiar for most of the included race-car drivers. However, a previous study that evaluated the role of familiarity with a particular route in modulating cerebral activations during a passive driving task demonstrated that brain response was higher in the sample with no direct experience on the specific track [18]. The authors suggested that this may depend on a reduction in levels of effort and attention needed to drive on known tracks in more expert individuals. In this perspective, their findings support the exclusion of a major role of the attention level in determining results described in the present work.

Finally, it should be kept in mind that, while the use of a passive task, rather than an active one, undoubtedly present some disadvantages, it also offer important advantages, including the possibility to avoid artifacts associated with movements in the scanner and to avoid potential confounding factors related to the different skills level of the experimental groups. In this respect, behavioral pilot observations obtained using a Formula One driving simulator available at Formula Medicine in Viareggio, clearly indicated that naïve drivers experience major difficulties in driving a racing car even in a simulated environment, making it impossible to use an active task if not only after a very extensive training. Furthermore, previous studies that examined brain response during passive and active driving, support the assumption that these two conditions share very similar functional substrates [17-19], and thus corroborate the reliability of a passive observation paradigm in studying this complex behavior.

4.3. Conclusions

The present study shows that during a passive racing car driving task professional and naïve drivers are characterized by different brain response patterns, with a significantly stronger recruitment of prefrontal cortex and motor control devoted areas in the first group and a greater visual cortex involvement in the naïve individuals. The observed results indicate that although both professional and naïve drivers possess the basilar knowledge needed for a general driving attitude, only the former are specifically trained in driving race-cars and can effectively compare their motor repertoire and expertise with specific situations presented in a Formula One driving task.

Finally, these results have some more general relevant methodological implications. First, they support the reliability of approaches based on ISC analysis in studying driving behavior or, more in general, complex human behaviors. Indeed, this data driven method may be extremely useful when complex naturalistic visual or auditory stimuli are involved, as in the case of video-clips depicting sport-related activities. Second, our results indicate the need to carefully evaluate the type of driving task and the particular expertise of the population enrolled in a study aimed at exploring the brain functional correlates of driving. In fact, the existence of different levels of expertise with certain vehicles or driving styles within an experimental sample may represent a relevant confounding factor.

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