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Expertise and injury experience in professional skiers modulate the ability to predict the outcome of observed ski-related actions

Alice Rossi Sebastiano [a], Karol Poles [a], Monica Biggio [b], Marco Bove [b], Marco Neppi-Modona [a], Francesca Garbarini [a,c], Carlotta Fossataro [a,*]

[a] *MANIBUS Lab, Department of Psychology, University of Torino, Torino, Italy*
[b] *Department of Experimental Medicine, Section of Human Physiology, University of Genoa, Genoa, Italy*
[c] *NIT, Neuroscience Institute of Turin, Turin, Italy*

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ABSTRACT

Professional athletes, compared to beginners, can better predict the outcome of sport-related observed movements, via mirror motor-system modulations (motor resonance). Furthermore, motor-system inhibition occurs when observing other people experiencing pain (pain resonance). Here we investigated whether observing sport-related actions, whose outcome can lead or not to a painful experience, results into different prediction performances depending on expertise and history of injury. Experiment 1 revealed that professional skiers, relative to beginners, show greater prediction accuracy but slower reaction times. Experiment 2 revealed that, among professional skiers, those previously injured, compared to uninjured ones, are slower in predicting the outcome of the observed action when it actually leads to an injury. We hypothesize that such results could be explained by an automatic activation of both motor and pain resonance mechanisms in the onlooker, inducing a sort of experience-dependant freezing response while observing actions likely leading to an injury.

1. Introduction

In order to safely and efficiently interact with a dynamic environment, evolution has equipped us with the ability to predict the outcome of executed and observed actions. In case of observed actions, compelling evidence suggests that such predictive ability relies on an inner motor simulation mechanism [i.e., motor resonance, see (Buccino et al., 2013; Rizzolatti & Craighero, 2004; Urgesi, Moro, Candidi, & Aglioti, 2006)]. Additionally, the anticipation of an action course depends upon one's own motor repertoire (Buccino et al., 2004) and is modulated by motor experience (Karlinsky, Zentgraf, & Hodges, 2017). Within this research domain, professional and non-professional athletes represent ideal experimental samples to investigate the influence of the observer's motor expertise on the ability to predict the outcome of observed actions. Indeed, a growing body of evidence suggests that professional athletes, as compared to beginners, can better predict the outcome of sport-related observed movements (Aglioti, Cesari, Romani, & Urgesi, 2008; Bove et al., 2017; Calvo-Merino, Grèzes, Glaser, Passingham, & Haggard, 2006; Tomeo, Cesari, Aglioti, & Urgesi, 2013). This ability is subserved by the modulation of motor resonance mechanisms, with athletes showing a greater activation of the motor system, relative to beginners (Balser et al., 2014; Karlinsky et al., 2017; Özkan, Pezzetta, Moreau, Abreu, & Aglioti, 2019). Moreover, studies employing transcranial magnetic stimulation (TMS) revealed an experience-dependant effect on motor resonance, with elite professionals showing a time-specific modulation of motor activation during observation of erroneous sport-related actions. For instance, Aglioti and colleagues showed that elite basketball players, but not expert watchers or beginners, present higher corticospinal excitability of the motor cortex while observing erroneous shots, as compared to correct ones (Aglioti et al., 2008). Interestingly, this increase only occurs at the instant when, in the erroneous shot, the contact between the hand and the ball is crucial to predict the fate of the player's shot.

In addition to these modulatory effects, a different resonant mechanism has shown to contribute to the modulation of motor system activation, i.e., pain resonance. It has been demonstrated that the observation of pain experience leads to motor system inhibition, similarly to what happens during the direct experience of pain (Avenanti, Minio-Paluello, Minio Paluello, Bufalari, & Aglioti, 2006, 2005; Avenanti, Minio-Paluello, Bufalari, & Aglioti, 2009; Avenanti,

* Corresponding author. Carlotta Fossataro Psychology Department, University of Turin Via Verdi 10, 10124, Turin, Italy.
E-mail address: carlotta.fossataro@unito.it (C. Fossataro).

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Minio-Paluello, Sforza, & Aglioti, 2009; Avenanti & Aglioti, 2006; Bucchioni et al., 2016; Bufalari, Aprile, Avenanti, Russo, & Aglioti, 2007; Farina, Tinazzi, Le Pera, & Valeriani, 2003; Valeriani et al., 2008). Furthermore, a pain resonance effect has been observed also at a behavioural level, with slower reaction times when participants are asked to press computer keys while observing painful compared to neutral scenes (Morrison, Poliakoff, Gordon, & Downing, 2007). These findings have been interpreted advocating the activation in the observer of a pain-resonant sensorimotor representation of the observed action.

Pain resonance mechanisms have been proposed to subserve different higher cognitive functions, such as understanding and empathizing with others' sufferance [for e.g., see (Avenanti & Aglioti, 2006)]. From an evolutionary perspective, pain resonance could also have the function of providing humans with the ability to anticipate whether an action course leads to a painful experience or not. If so, as motor expertise shapes motor resonance (Aglioti et al., 2008), a previous experience of a painful injury should similarly modulate pain resonance mechanisms.

In the present study we investigated whether i) skiing expertise enhances the ability to predict ski-related actions outcomes (Experiment 1) and ii) a previous experience of injury influences the ability to predict ski-related injury outcomes in professional skiers (Experiment 2). In line with previous literature, in Experiment 1 we expected to observe a better prediction performance in professional relative to beginner skiers. In Experiment 2, we predicted a greater pain resonance effect (indexed by slower reaction times when the fall led to an injury as compared to no-injury falls) in professional skiers who had previously experienced an injury, relative to non-injured ones.

2. Materials and methods

2.1. Participants

Sample size was estimated with an a-priori power analysis conducted on preliminary data employing G*Power software (www.psycho.uniduesseldorf.de/abteilungen/aap/gpower3). Specifically, 5 injured and 5 non-injured professional skiers underwent a pilot experiment in which reaction times (RTs) were collected while they performed the very same task of Experiment 2. Since we were interested in the interaction effect between the variables Group and Condition in Experiment 2, we computed the difference between conditions for each group and calculated the effect size (dz) on the basis of these data. Then, we estimated the required sample numerosity to reach a power of 0.8 (dz = 0.81, actual power = 0.8). The output of the power analysis showed that twenty participants per group were required. Hence, in order to keep the sample size equal between experiments, we recruited a total of forty participants (20 per group) for each experiment.

In Experiment 1, according to the categorization of skiing abilities identified by the A.M.S.I (Association of Italian Ski Instructors, https://www.amsi.it/en/the-association). twenty participants (13 women; mean age ± sd: 27.8 ± 8.26; mean years of education ± sd: 15.05 ± 2.04) with sparse or no experience in skiing were assigned to the *beginners*' group; the remaining twenty participants (11 women; mean age ± sd: 25 ± 6; mean years of education ± sd: 15.25 ± 1.83) were categorized as professional skiers and therefore assigned to the *professionals*' group.

A different sample of thirty-eight professional skiers agreed to participate in Experiment 2. Nineteen of them (9 women; mean age ± sd: 23.42 ± 2.09; mean years of education ± sd: 14.95 ± 1.81) had never suffered severe injuries to their lower limbs while skiing, nor they had to stop practicing for more than 28 days because of an injury and were therefore assigned to the *non-injured professionals*' group. The remaining nineteen participants (9 women; mean age ± sd: 24.21 ± 2.20; mean years of education ± sd: 14.52 ± 1.71) were professional skiers who, due to a severe injury to at least one of their legs, underwent surgery and/or followed a rehabilitation program that caused absence from training or competition for more than 28 days (Flørenes, Nordsletten, Heir, & Bahr, 2012; Tarka et al., 2019) and were assigned to the *injured professionals*' group. Reported injuries comprised anterior cruciate lesions, collateral ligament or meniscus lesions, tibial and fibular fractures. At the time of the experiment, none of the injured professionals were undergoing a rehabilitation program and at least one year had passed since the time of injury.

All participants were right-handed except for 2 beginners and 2 professionals in Experiment 1 and 1 non-injured and 2 injured professionals in Experiment 2, who were left-handed, according to the Edinburgh Handedness Inventory – short form (Veale, 2014). All participants gave their informed consent to participate in the study, which was approved by the Ethical Committee of the University of Turin (prot. n° 251,260).

2.2. Apparatus, stimuli and procedure

Experimental stimuli of both Experiment 1 and 2 consisted in a series of short movies depicting extracts from alpine ski races. See examples of the employed stimuli here: https://data.mendeley.com/datasets/tcxymbxbt2/draft?a=7ed94ebb-8d97-465f-8d0a-5d9812376129.

Participants sat comfortably at a desk facing a computer screen (15 inches) distant 80 cm and were asked to press a key on the computer keyboard with their right hand in response to the video (see details about each experiment's task below). Response accuracy and reaction times (RTs) were collected. For stimuli administration and data collection the software PsyToolkit was used (Stoet, 2010, 2017).

2.2.1. Experiment 1

In Experiment 1, each trial began with a white fixation cross centred on a black computer screen for 2 s, followed by a 3 s ski video (75 frames of 40 ms each) which preceded a black slide with a central white question mark, displayed for 2 s (total trial duration = 7 s) (see Fig. 1). Professional skiers and beginners underwent 8 blocks of 10 trials in a counterbalanced order, so that half of the participants were presented with 8 blocks in sequence (1-2-3-4-5-6-7-8), while the other half were presented with the same blocks in the inverted sequence (8-7-6-5-4-3-2-1). Within each block, the trials of the experimental conditions (see below) were presented in a pseudo-random order.

Ski videos comprised: i) 30 race extracts showing a skier who was about to fall (*fall* condition); ii) 30 race extracts showing a vacillating skier whose course of action did not lead to a fall (*no-fall* condition); iii) 20 race extracts showing an athlete skiing (catch trials). Videos were interrupted before the ending of the action and replaced by the question mark slide. Videos were accurately selected and cut by an expert professional skier who was blind to the aim of the study. The actions observed in the videos consisted of three phases: an initial phase wherein the athlete was skiing, a second phase wherein the athlete performed an erroneous movement, and a third phase wherein the athlete could either fall (fall trials) or employ fast online motor corrections to avoid the fall (no-fall trials). The videos were interrupted at the end of the second phase, so that the observer could not see whether the skier actually fell or not. Participants were asked to press the leftward or rightward arrow keyboard keys with the index finger of their right hand to indicate whether the skier's course of action led to a fall or not, as fast and accurately as possible.

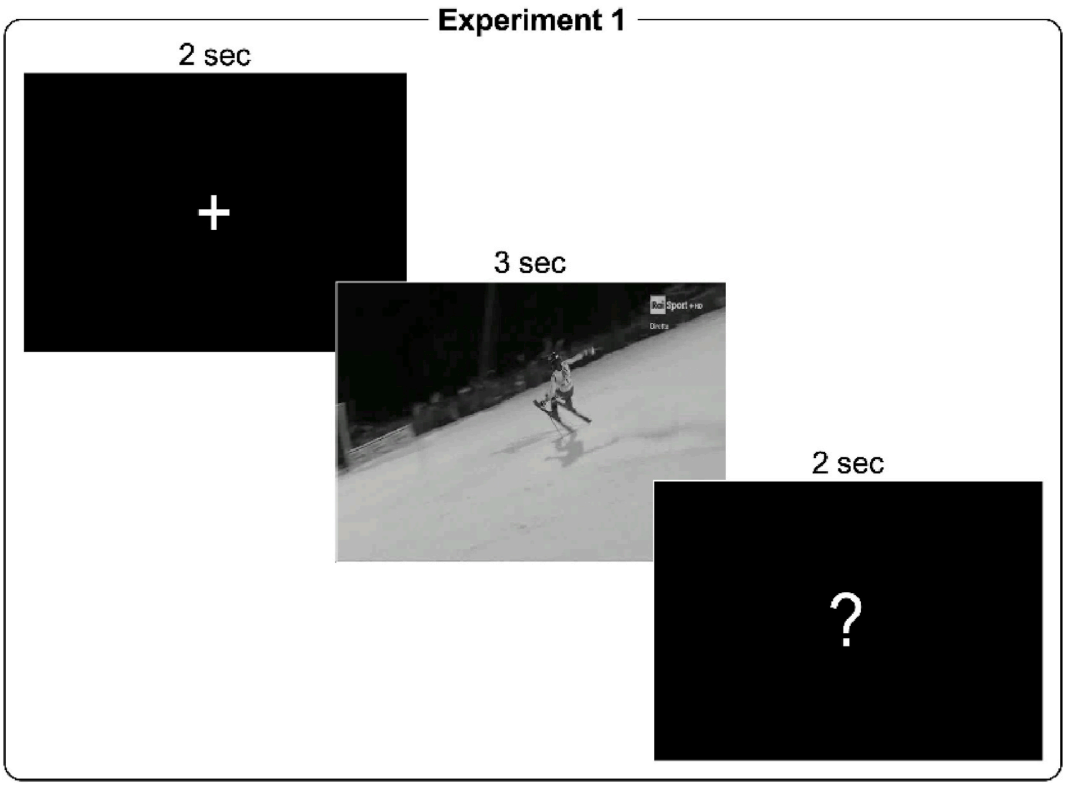

Fig. 1. Experiment 1. Each trial began with a white fixation cross centred on a black screen for 2 s, followed by a 3 s ski video (75 frames of 40 ms each) and a black slide with a centred white question mark, displayed for 2 s (trial total duration = 7 s). The ski video showed ski races extracts wherein a skier was about to fall (*fall* condition; 30 trials) or was vacillating but the course of action did not actually lead to a fall (*no-fall* condition; 30 trials). Additionally, 20 catch trials showing ski races extracts without any vacillation were presented as well. Beginners and professional skiers were asked to predict whether the athlete fell or not, by pressing one of two computer keyboard keys.

2.2.2. *Experiment 2*

The procedure of Experiment 2 was similar to that of Experiment 1. Indeed, each trial began with the white fixation cross centred on the black screen for 2–8 s, followed by a ski video which lasted 1–7 s and was then replaced by the question mark slide for 2 s (trial total duration = 11 s) (see Fig. 2). Participants underwent 12 blocks of 5 trials in a counterbalanced order, so that half of the participants were presented with 12 blocks in sequence 1-2-3-4-5-6-7-8-9-10-11-12, while the other half were presented with the same blocks in the inverted sequence (12-11-10-9-8-7-6-5-4-3-2-1). Within each block, the trials of the experimental conditions (see below) were presented in a pseudo-random order. Ski videos comprised 60 ski races extracts wherein professional skiers incurred in a fall. In 50% of the trials the observed fall actually led to a painful injury (*injury* condition), while in the remaining 50% the fall did not lead to an injury (*no-injury* condition). Differently from Experiment 1, videos were not interrupted before the fall, so that participants observed the entire ski action. Specifically, the action consisted of three phases (i.e., phase one: the athlete was skiing; phase two: the athlete performed an error; phase three: the athlete fell). The videos were cut at the end of phase three, when the athlete had already fallen down, but the actual consequences of the fall were not clear yet. Participants were asked to press one of two keyboard keys (leftward/rightward arrow) with their right hand to guess whether the skier incurred into an injury or not after the observed fall, as fast and accurately as possible.

3. Data analysis

Data analyses were performed on the percentage of correct responses (accuracy) and on mean RTs, employing Statistica Software (StatSoft, release 8). Note that only RTs to correct responses were included in the analysis. The Shapiro-Wilk test revealed that normality assumptions were not violated for any dataset (p always >0.05), except for the mean RTs of the no-fall condition (Experiment 1). Despite this, in order to employ the same statistical analyses for the different datasets and experiments, we decided to perform parametric ANOVAs (see, e.g., Christensen et al., 2010; Kaplan, Enticott, Hohwy, Castle, & Rossell, 2014), as they are known to be quite insensitive to moderate deviations from normality (Glass, Peckham, & Sanders, 1972; Lix, Keselman, & Keselman, 1996). To confirm the ANOVA results, we also conducted nonparametric Mann-Whitney tests on the dataset whose residual distribution was not normal.

3.1. *Experiment 1*

Accuracy percentages and mean RTs were entered in a 2 × 2 ANOVA with Group (two levels: professionals, beginners) as between-subject factor and Condition (two levels: fall, no-fall) as within-subject factor. Moreover, to confirm the ANOVA results (see 4.1), we collapsed the mean RTs of the two conditions for each group and compared them by means of a Mann-Whitney test. We reported p-values and effect sizes (η^2). According to the benchmarks provided by Cohen (Cohen, 1988), we define effects as small ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$), and large ($\eta^2 = 0.14$).

Since the ANOVAs run on accuracy and RTs showed a specular result (i.e., main effect of Group; see 4.1), we collapsed the accuracy of the two conditions (fall/no-fall) within each group and ran two separate one

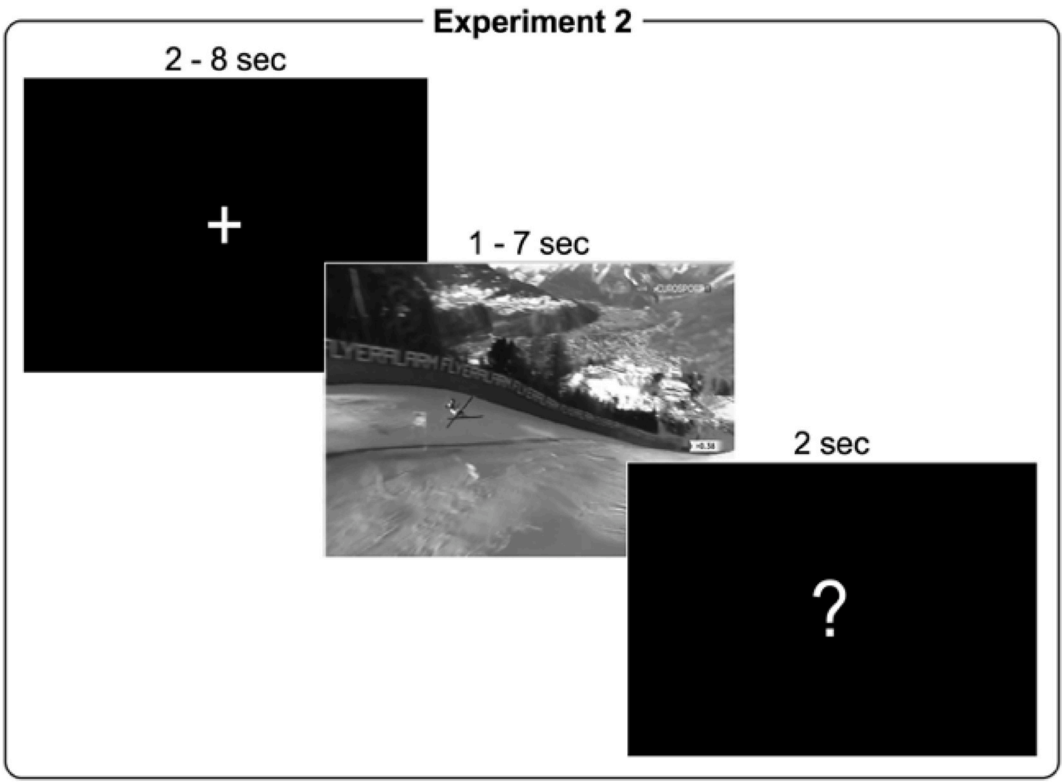

Fig. 2. Experiment 2. The procedure was similar to that of Experiment 1. A white fixation cross (2–8 s) was followed forthwith by a ski race extract (1–7 s), and then by a black slide with a central white question mark (2 s; trial's total duration = 11 s). The ski races extracts showed professional skiers incurring in a fall. In 50% of the trials the observed fall actually led to a painful injury (*injury* condition), while in the remaining 50% the fall did not lead to an injury (*no-injury* condition). Professional skiers were asked to indicate whether the accident led to an injury or not by pressing one of two computer keyboard keys.

sample t-tests (test value: 50%) on these values to investigate whether the two groups' responses were above or below the chance level. Bonferroni correction was applied to control for multiple comparisons. Finally, to test for the presence of a speed-accuracy trade off, we ran, separately for each group, a Pearson correlation between accuracy percentages and RTs. Bonferroni correction was applied to control for multiple comparisons.

3.2. Experiment 2

Accuracy percentages and mean RTs values were entered in a 2 × 2 ANOVA with Group (two levels: injured professionals, non-injured professionals) as between-subject factor and Condition (two levels: injury, no-injury) as within-subject factor. Post-hoc comparisons were performed by means of the Newman-Keuls test. We reported p-values and effect sizes (η^2). According to the benchmarks provided by Cohen (Cohen, 1988), we define effects as small ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$), and large ($\eta^2 = 0.14$)

Furthermore, we ran four separate one sample t-tests against the chance level (separately for each condition and for each group) to investigate whether the difference highlighted by the significant Condition × Group interaction in RTs (see 4.2) was mirrored by the accuracy levels being above or below the chance level. Bonferroni correction was applied to control for multiple comparisons. Finally, to rule out that the results obtained in RTs could be explained by the participants' accuracy, we performed correlation analyses separately for each condition and for each group. Bonferroni correction was applied to control for multiple comparisons.

4. Results

4.1. Experiment 1

Accuracy results showed a significant main effect of Group ($F_{1,38} = 66.84$; $p < 0.0001$; $\eta^2 = 0.64$; see Fig. 3A), with professionals performing significantly better than beginners. Unexpectedly, although it did not reach statistical significance, we found a trend for a Condition × Group interaction ($F_{1,38} = 3.39$; $p = 0.07$; $\eta^2 = 0.08$), with professional athletes showing higher accuracy in the no-fall compared to the fall condition. Mean accuracy (%) ± sd in the no-fall condition: professionals, 68.67 ± 16.4; beginners, 41.5 ± 15; in the fall condition: professionals, 54.67 ± 16.42; beginners, 42.83 ± 12.58.

RTs results revealed a significant main effect of Group ($F_{1,38} = 21.31$; $p < 0.0001$; $\eta^2 = 0.36$; see Fig. 3B), with professionals being slower than beginners [mean RT (s) ± sd: professionals, 3.41 ± 0.31; beginners, 2.87 ± 0.42]. Moreover, the Mann-Whitney test on mean RTs confirmed the ANOVA results, revealing a significant difference between groups ($U = 55$; $p < 0.0001$).

The one-sample t-tests highlighted that the beginners' responses were significantly below the chance level ($t_{19} = -4.49$; $p = 0.002$; d =

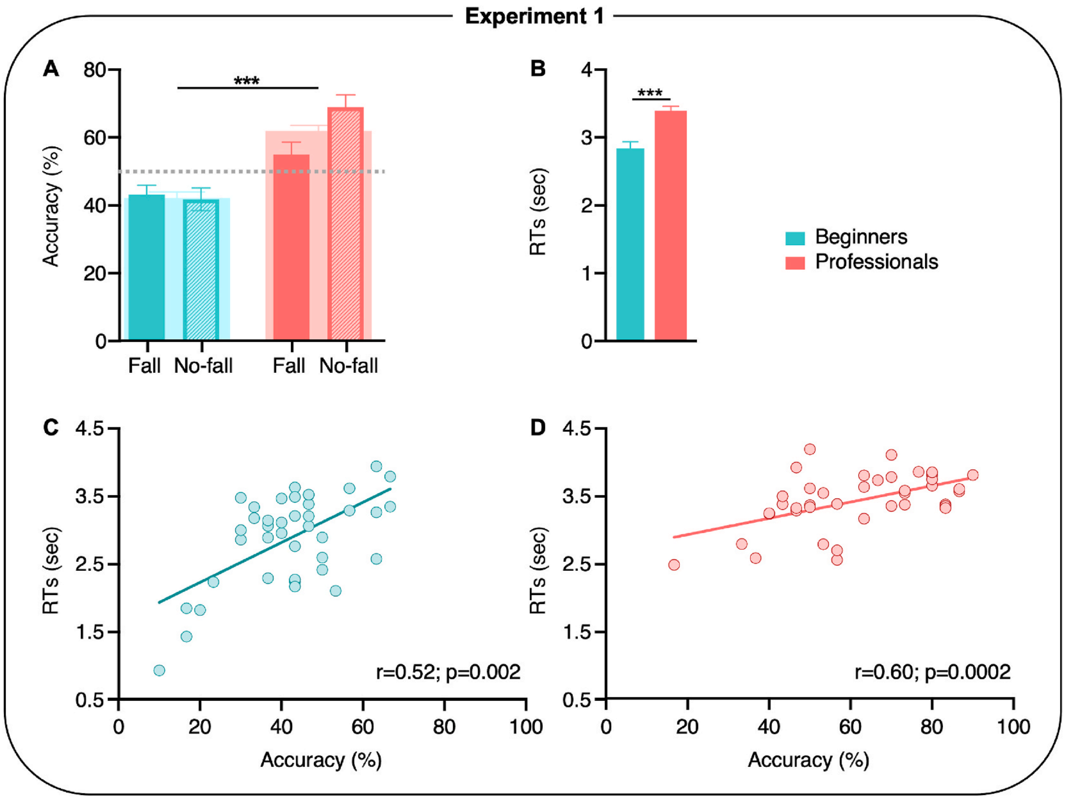

Fig. 3. Experiment 1 results. Vertical bars represent accuracy percentages (panel A) and mean RTs (panel B) of beginners (light blue) and professionals skiers' (light red) responses. Panel A: solid bars represent the response accuracy percentage in the fall condition; dashed bars represent the response accuracy percentage in the no-fall condition; the larger light-coloured columns in the background represent the main effect of Group; the grey dotted line indicates the chance level of accuracy. Panel C and D represent the correlation between accuracy and RTs respectively in the beginners' (light blue) and in the professionals' (light red) group. Error bars indicate the standard error of the mean (SEM); the asterisks a significant difference (***: $p < 0.001$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

1.01), whereas the professionals' ones were significantly above it ($t_{19} = 7.17$; $p = 0.002$; $d = 1.61$). Finally, the correlation analyses confirmed the presence of a speed-accuracy trade off, with a significant positive correlation between accuracy and speed of response (professional skiers: $r = 0.52$; $p = 0.002$; beginners: $r = 0.60$; $p = 0.0002$), indicating that the more accurate the response was, the slower the RTs.

4.2. Experiment 2

Accuracy results showed a significant main effect of Condition ($F_{1,36} = 32.87$; $p < 0.0001$; $\eta^2 = 0.48$), with participants being more accurate in the no-injury [mean accuracy (%) ± sd: 77.02 ± 12.47] than in the injury condition (54.91 ± 14.12)

RTs results revealed a significant main effect of Condition ($F_{1,36} = 12.56$; $p = 0.001$; $\eta^2 = 0.23$), with participants being slower in the injury compared to the no-injury condition. Crucially, a significant Condition × Group interaction ($F_{1,36} = 5.17$; $p = 0.02$; $\eta^2 = 0.10$; see Fig. 4) was found, explained by significantly slower RTs of injured professionals in the injury condition compared to all the other conditions (p always <0.05). Conversely, no difference emerged between conditions in the non-injured professionals' group. Mean RT (s) ± sd in the injury condition: injured professionals, 4.56 ± 0.42; non-injured professionals, 4.13 ± 0.76; in the no-injury condition: injured professionals, 4.14 ± 0.49; non-injured professionals, 4.04 ± 0.5.

The one-sample t-tests performed on the accuracy in the no-injury conditions of both the injured and non-injured groups were significant (injured: $t_{18} = 8.65$, $p = 0.004$, $d = 1.98$; non-injured: $t_{18} = 10.12$, $p = 0.004$, $d = 2.32$), while those performed on the accuracy in the injury conditions of both groups were not significant (injured: $t_{18} = 1.77$, $p = 0.36$, $d = 0.41$; non-injured: $t_{18} = 1.25$, $p = 0.92$, $d = 0.29$). This result is in line with the main effect of condition revealed by the accuracy results (see above). Importantly, no significant correlation was found between RTs and accuracy (p value always >0.09), confirming that the results obtained in RTs were not explained by the participants' accuracy.

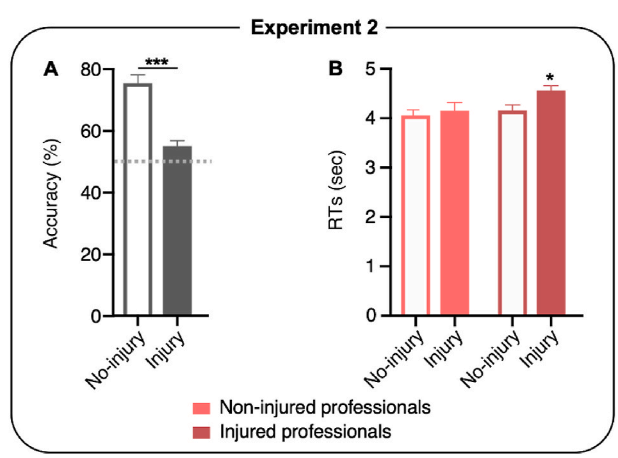

Fig. 4. Experiment 2 results. Vertical bars represent mean response accuracy percentages (panel A) and mean RTs (panel B) in the no-injury (empty bar) and injury (solid bar) conditions. Panel A: the grey dotted line indicates the chance level of accuracy. Panel B: light red bars represent non-injured professionals' mean RTs; dark red bars represent injured professionals' mean RTs. Error bars indicate the standard error of the mean (SEM) and the asterisk a significant difference (*: $p < 0.05$; ***: $p < 0.001$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5. Discussion

In the present study, we investigated whether motor expertise and injury experience modulate the ability to predict the outcome of observed ski-related actions. More specifically, since previous evidence highlights that motor expertise shapes motor resonance (Aglioti et al., 2008; Calvo-Merino et al., 2006; Pedullà et al., 2020), we addressed whether previous painful experiences can modulate pain resonance. We designed two experiments aimed, respectively, to i) replicate the expertise-dependent effect on motor resonance in the skiing sports field (Experiment 1) and ii) investigate the effect that a ski-related injury experience has on pain resonance in professional skiers (Experiment 2). Our findings reveal that prediction speed and accuracy of observed actions' outcome are modulated both by motor expertise and history of injury experience.

In particular, the results of Experiment 1 show that professional skiers, relative to non-professional ones, are more accurate, yet slower, when predicting the occurrence of a fall. Interestingly, while professional skiers' responses are significantly above chance level, beginners' responses are significantly below chance level. Furthermore, the more accurate the response is, the slower the RTs. Previous evidence suggests that responses speed up at the expense of accuracy, so that guess behaviour is associated with faster but random responses (Börger, 2016; Dutilh, Wagenmakers, Visser, & Van Der Maas, 2011; Schoutev & Bekker, 1967; Standage, Blohm, & Dorris, 2014). Accordingly, the RTs of Experiment 1 are explained by a speed-accuracy trade-off. This evidence is in accordance with that of previous studies suggesting that motor resonance mechanisms rely on motor experience and are boosted by expertise. Such expertise-dependent effects on motor resonance have been previously observed at a physiological level, with professional athletes showing grater activation of the motor system than beginners when observing sport-related actions (Aglioti et al., 2008; Balser et al., 2014; Calvo-Merino et al., 2006; Karlinsky et al., 2017; Tomeo et al., 2013; Özkan et al., 2019). These effects also have a behavioural counterpart, with professionals resulting more accurate than beginners in predicting the outcome of observed actions (Aglioti et al., 2008; Bove et al., 2017; Tomeo et al., 2013). According to these studies, it seems that the athletes' motor system is capable of simulating more accurately the course of observed actions due to higher motor expertise, inducing a greater activation of the mirror system circuit, as well as an enhanced motor prediction performance. In the present study, by employing a motor prediction task, we demonstrated, for the first time in the skiing sport field, an expertise-dependant effect on motor resonance at a behavioural level.

Interestingly, when analysing the accuracy of response data of Experiment 1, we unexpectedly found a trend for a significant interaction between group and condition ($p = 0.07$), with professional skiers showing higher prediction accuracy in the no-fall compared to the fall condition. Although the interaction did not reach the significance level, the effect size is medium ($\eta^2 = 0.08$). Thus, we can speculate that this effect may be explained by the professionals' expertise, as professional skiers are better than beginners at employing fast online motor corrections to avoid a fall, and these postural adjustments are implemented into their motor repertoire. Hence, it is possible that, in the no-fall condition, professional skiers are better in recognizing the above-mentioned motor adjustments occurring in the observed movement and can use them as a cue to better predict the outcome of the observed action. However, further studies employing larger samples are needed to corroborate the validity of this hypothesis.

In Experiment 2 we investigated the effect of a previous experience of injury on pain resonance mechanisms when estimating the probability of a painful outcome of an observed action course. Our results highlight that slower RTs were measured in injured as compared to non-injured professionals when the observed action lead to a painful outcome. Importantly, in Experiment 2 the RTs were not related to the accuracy levels, ruling out a speed-accuracy trade off. There is compelling evidence that the observation of others experiencing pain decreases the amplitude of motor evoked potentials (MEPs) (Avenanti et al., 2006, 2005; Avenanti, Minio-Paluello, Sforza, & Aglioti, 2009; Avenanti & Aglioti, 2006; Bucchioni et al., 2016; Bufalari et al., 2007), similarly to when pain is actually experienced (Farina et al., 2001; Fossataro et al., 2020, 2018; Le Pera et al., 2001). Additionally, several studies employing neuroimaging techniques confirmed the presence of motor system inhibition both while observing pain inflicted to others (Valeriani et al., 2008) and while experiencing it directly (Burns, Chipchase, & Schabrun, 2016; Farina et al., 2003; Hodges, Coppieters, MacDonald, & Cholewicki, 2013; Hodges & Tucker, 2011).

Interestingly, Morrison and colleagues showed that pain resonance modulations on the motor system have also a behavioural counterpart (Morrison et al., 2007). By collecting RTs following the observation of videos of noxious stimuli delivered on the hands, they revealed that pain observation modulates motor reactivity, slowing the approach movements of the responsive hand. This effect may reflect a modulation of the onlooker's motor system, i.e., the simulation of a freezing response. The results of Experiment 2 are in line with this evidence, showing that when a potentially painful action course is displayed, seemingly a freezing response is activated in the onlooker, resulting in a slower reactivity of the motor system, as measured by slower RTs.

In an evolutionary perspective, 'freezing' belongs to a repertoire of species-specific fear responses aimed to avoid pain, which are activated when an individual encounters threatening stimuli or situations (Roelofs, 2017). More specifically, it consists in the cessation of movement when neither hiding nor escaping are viable options (Blanchard, Griebel, Pobbe, & Blanchard, 2011). Previous evidence suggested a pivotal role of the amygdala in mediating the freezing and defensive reactions (Roelofs, 2017). In particular previous studies showed that the projections from the amygdala to the periaqueductal gray (PAG) triggers the activation of defensive responses, such as freezing reactions (Fossataro et al., 2020; Hermans, Henckens, Roelofs, & Fernández, 2013; Martins, Tavares, & Warren, 2017; Tovote, Fadok, & Lüthi, 2015). In the context of sports injury, the aversive stimulus is not an incoming threat from which one can escape or that one can fight, but rather it represents a painful situation in which the most effective protective reaction should be to remain still in order to avoid further pain. Hence, the activation of the freezing response may represent the most appropriate response. Hence, in agreement with studies that demonstrated the activation of the very same network during both the actual experience of pain and the observation of pain in others, we may speculate a crucial involvement of the amygdala-PAG pathway in mediating the motor system inhibition that we measured at the behavioral level.

The activation of a freezing response during the observation of other people experiencing pain may subserve different functions, such as empathizing with their sufferance [e.g., see (Avenanti & Aglioti, 2006)] or being able to anticipate whether an action course leads to a painful experience or not. Crucially, we also found that a previous experience of an injury further enhances this resonant mechanism, resulting in a decrease of motor reactivity (reflecting an increase in motor inhibition) when a potentially painful action course is observed. Indeed, injured professionals were significantly slower than non-injured ones when responding to a potentially painful scene, despite accuracy being comparable in the two groups. Hence, one may hypothesize that, following a traumatic sport-related injury, such a defensive mechanism, which has an adaptive nature, might have maladaptive effects in the context of sport competitions, negatively influencing the athlete's performance. Although surgery and rehabilitative programs are effective in restoring motor function to a normal level, it is well known that a number of professional athletes having suffered an injury are unsuccessful in regaining the pre-injury competitive level (Ardern, Taylor, Feller, & Webster, 2014; Paterno, Flynn, Thomas, & Schmitt, 2018). It is possible to speculate that this could be the consequence of the automatic activation of an experience-dependent freezing mechanism triggered by the fear of getting injured again. Future studies should investigate this hypothesis in order to develop rehabilitation training procedures specifically aimed to inhibit this fear-related defensive reaction.

Despite the evidence that we report, some limitations of our study must be acknowledged. Indeed, for both Experiment 1 and Experiment 2, only behavioural measures were collected. Future studies should employ also neurophysiological measures aimed to reveal the neurobiological substrates of these motor and pain resonance mechanisms. For instance, it should be assessed whether higher prediction ability in professionals compared to beginners is mirrored by a modulation of error-detection electrophysiological markers. Furthermore, the primary motor cortex excitability should be measured by recording MEPs amplitude during the very same tasks employed here, to investigate whether the observation of a fall leading to an injury to a specific body district (e.g., superior or inferior limb) induces a specific muscle inhibition measured from the corresponding body district. Finally, another interesting issue to address could be the relation between the freezing response highlighted here and the severity of injury or time since injury.

6. Conclusion

The results of our study suggest that motor expertise as well as pain experience have a modulatory (boosting) effect on the ability to predict the outcome of observed motor actions, subserved by motor and pain resonance mechanisms. Motor expertise enhances prediction accuracy of action outcome and pain experience increases our ability to anticipate a possible injury, via a freezing mechanism, i.e., slowing down the approach movements towards potential external threats. Furthermore, the presence of an abnormal freezing response in injured athletes may constitute the basis for future studies aimed at investigating whether this inhibitory motor mechanism may limit the ability of injured athletes to regain the pre-injury level of performance and whether it can be downregulated by ad hoc training procedures.

Declarations of interest

None.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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