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Affordances after spinal cord injury

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Abstract

Spinal cord injury can cause cognitive impairments even when no cerebral lesion is appreciable. As patients are forced to explore the environment in a non-canonical position (i.e., seated on a wheelchair), a modified relation with space can explain motor- related cognitive differences compared to non-injured individuals. Peripersonal space is encoded in motor terms, that is, in relation to the representation of action abilities and is strictly related to the affordance of reachability. In turn, affordances, the action possibilities suggested by relevant properties of the environment, are related to the perceiver's peripersonal space and motor abilities. One might suppose that these motor- related cognitive abilities are compromised when an individual loses the ability to move. We shed light on this issue in 10 patients with paraplegia and 20 matched controls. All have been administered an affordances-related reachability judgement task adapted from Costantini, Ambrosini, Tieri, Sinigaglia, and Committeri (2010, Experimental Brain Research, 207, 95) and neuropsychological tests. Our findings demonstrate that patients and controls show the same level of accuracy in estimating the location of their peripersonal space boundaries, but only controls show the typical overestimation of reaching range. Secondly, patients show a higher variability in their judgements than controls. Importantly, this finding is related to the patients' ability to perform everyday tasks. Finally, patients are not faster in making their judgements on reachability in peripersonal space, while controls are. Our results suggest that not moving freely or as usual in the environment impact decoding of action-related properties even when the upper limbs are not compromised.

Introduction

Spinal cord injury (SCI) is a neurological condition that causes motor and/or sensory impairments (McDonald & Sadowsky, 2002). Depending on the lesion level, impairments can be limited to the inferior sector (paraplegia) or involve the entire body starting from the cervical vertebrae (quadriplegia) (McDonald & Sadowsky, 2002). The most common aetiology of non-congenital SCI comprises traumatic events, such as car accidents, with a reported incidence between 236 and 4,187 cases per million (Lee, Cripps, Fitzharris, & Wing, 2014).

Growing evidence is showing that patients with traumatic SCI can manifest cognitive consequences of the lesion even when no lesion to the brain is appreciable (Davidoff, Roth, & Richards, 1992). For instance, SCI patients use a different, non- motor, strategy to imagine body rotations than non-injured individuals, regardless of the spinal lesion level (Fiori et al., 2013). Further, they perceive an elongation in their body representation, again independent from the lesion level (Fuentes, Pazzaglia, Longo, Scivoletto, & Haggard, 2013). This body representation disorder might be related to the distorted interaction between the patient and the environment because they are forcedly sitting on the wheelchair. Moreover, they are no longer able to switch from sitting and standing, continuously updating and adapting their spatial coordinates to the environment.

Importantly, motor-related cognitive skills also include the interaction with objects involving motor acts. The concept of ‘affordances’ has been introduced to describe the properties of the environment that furnish the viewer with opportunities to perform actions such as walking (Gibson, 1979), reaching, and grasping (Tucker & Ellis, 1998). In other words, a cup is not only a cup, but also an object that one can reach and grasp. For instance, it has been shown that the vision of objects with relevant congruent motor features, such as a handle in a graspable position, can prime compatible actions (Tucker & Ellis, 2004) and facilitate processing of relevant affordance-related semantic features of the objects, such as the verbs denoting their function (Costantini, Ambrosini, Scorolli, & Borghi, 2011). Importantly, the perception of affordances depends on the perceiver's motor abilities and the state of his/her body. Indeed, it has been shown that postural restraints and different types of locomotion that interferes with participants' motor abilities may affect the accuracy of concurrent affordance-related judgements (Yasuda, Wagman, & Higuchi, 2014; Yu, Bardy, & Stoffregen, 2010; Yu & Stoffregen, 2012). Similarly, performing a simultaneous interfering motor task while naming pictures of a tool disrupts the affordance-related facilitation of the processing of relevant semantic features of the tool itself and interferes with its identification (Witt, Kemmerer, Linkenauger, & Culham, 2010).

Relevant to the concept of affordances is the notion of peripersonal space. Firstly identified in monkey and recently explored also in humans, peripersonal space can be functionally described as the space surrounding our bodies, in which we can easily reach objects and act upon them (Brozzoli, Makin, Cardinali, Holmes, & Farn`e, 2012). Peripersonal space is opposed to extrapersonal space, which extends beyond it and in which we cannot act directly upon objects without moving towards them or using tools to reach them. Peripersonal and extrapersonal areas are differently represented in the brain and refer to diverse frames of reference to encode sensory inputs (di Pellegrino & L´adavas, 2015). Peripersonal space is encoded in motor terms, that is, in relation to the representation of our body and actions and is thus strictly related to the affordance of reachability (Delevoye-Turrell, Bartolo, & Coello, 2010). It is interesting to note that, when using appropriate tools, space is flexible as far space can easily be remapped in near peripersonal space (Berti & Frassinetti, 2000). Congruently, recent experiments provide evidence that affordances are effective if the object is in the peripersonal space and if the subject can actually move his limb towards the target. This demonstrates that affordances are modulated by the appropriateness of the physical features of the object, its adequate location in space, and the objective possibility of the viewer to act on it (Ambrosini, Scorolli, Borghi, & Costantini, 2012; Cardellicchio, Sinigaglia, & Costantini, 2011; Costantini, Ambrosini, Tieri, Sinigaglia, & Committeri, 2010; Ferri, Riggio, Gallese, & Costantini, 2011).

In summary, affordances depend on both spatial perception and motor abilities. One might hypothesize that SCI can cause an impairment of patients' affordance perception and a consequent pervasive perturbation of their spatial coordinates due to the abrupt motor limitation that globally alters their perception and exploration of the environment. Even in case of paraplegia that preserves arms movements, the canonical exploration of space is prevented by the limited movements of the trunk and by the wheelchair that also prevents to approach objects in a natural fashion. As moving in the environment represents such a crucial component of human adaptation (Yasuda et al., 2014; Yu & Stoffregen, 2012; Yu et al., 2010), one might hypothesize that SCI causes quite rapidly a different spatial representation in patients with this clinical condition compared to normal subjects, inducing an impairment of the cognitive components involved in affordances and more in general in moving in space.

In this study, we explored this issue, whether individuals with lesions to the spinal cord, causing paraplegia, show a different representation of peripersonal space and a different perception of objects located in it. This might happen due to their different exploration of the environment, related to their inability to walk and engage in reaching movements using the whole body but not to their ability to move their hands. If our hypothesis is true, one would expect that individuals who do not explore the space in a canonical way, even when the ability to move the hands is retained, would not show particular effects associated to peripersonal space and thus to reachability affordances. On the contrary, if such effects were spared, individuals with spinal cord injuries would still be able to 'map' peripersonal space as controls do, suggesting that the change in environment exploration does not affect all motor-related cognitive skills. We also took into account cognitive abilities and clinical features of patients, as they might affect these individuals' motor-related skills.

Materials and methods

Participants

Ten patients with paraplegia have been enrolled in this study. Patients were referred from clinicians at the Unipolar Spinal Unit, ASST Grande Ospedale Metropolitano Niguarda, Milan, Italy. All participants were right-handed and had normal or corrected-to-normal vision. Detailed information about demographic features and neuropsychological screening of all participants is shown in Table 1. All patients presented with a lesion of traumatic aetiology (onset between 6 and 12 months) and restricted to the dorsal level of the spinal cord (clinical data are reported in Table 2). Exclusion criteria were severe cognitive impairments (basing on cognitive screening), central nervous system patholo- gies, abuse of alcohol or drugs, and comorbidity with psychiatric pathologies. In addition,

20 normally sighted gender-matched and age-matched, control participants were recruited from the pool of students of the Department of Brain and Behavioral Sciences, University of Pavia, Italy to take part in the experiment as controls.

Table 1. Descriptive statistics of demographic and neuropsychological variables for SCI patients and control participants

Measure (mean [SD])	SCI (n = 10)	Controls (n = 20)	t28	p
Demographic features				
Age (years)	42.4 (15.3)	35.0 (15.7)	1.236	.227
Education (years)	12.0 (2.1)	14.9 (1.8)	3.845	.001
Gender	1 male	4 males	–	.449a
Neuropsychological tests				
Mini Mental State Examination (cut off = 23.8)	29.3 (1.2)	29.3 (1.3)	0.047	.963
Phonemic fluency	30.0 (12.0)	44.7 (13.1)	2.968	.006
Semantic fluency	44.0 (9.4)	49.7 (13.9)	1.156	.257
Attentional matrices	52.6 (4.8)	49.2 (5.3)	1.729	.095
Frontal Assessment Battery	15.6 (1.4)	16.4 (0.7)	1.563b	.147b

Notes. Neuropsychological values indicate age- and education-corrected scores (see main text for references to normative values). aFisher’s exact test. bWelch’s t-test.

Table 2. Clinical data of patients enrolled in the study

Patient	Lesion level	SCIM	ASIA	Days since onset
SCI01	D5	22	A	196
SCI02	D9	32	A	361
SCI03	D10	21	A	147
SCI04	D7	33	B	222
SCI05	D8	20	C	95
SCI06	D3	28	C	288
SCI07	D4	15	C	187
SCI08	D10	17	C	244
SCI09	D4	15	C	430
SCI10	D5	22	A	200

Note. Lesion level indicates the spinal level of the injury (D = dorsal). SCIM = Spinal Cord Independence Measure scale (score range for our sample: 15–33, indicating a low level of independence). ASIA = American Spinal Injury Association Impairment Scale (Range for our patients: A = no motor nor sensory function preserved; B = partial sensory but not motor function preserved; C = some sensory and motor function preserved, indicating none of the patients had completely preserved functions). Days since onset: days passed from the injury to the neuropsychological screening.

The study has been conducted in accordance with the ethical standards of the Declaration of Helsinki, and informed consent was obtained from all participants prior to the experiment. The research protocol and the informed consent form have been approved by the Ethics Committee of Unipolar Spinal Unit, ASST Grande Ospedale Metropolitano Niguarda, Milan, Italy.

Task and procedure

All participants have been administered a neuropsychological screening including the Mini–Mental State Examination (MMSE; Measso et al., 1993), the Phonemic and Semantic Fluency tests (Novelli et al., 1986), the Attentional Matrices (Spinnler & Tognoni, 1987), and the Frontal Assessment Battery (FAB; Apollonio et al., 2005). Furthermore, all patients have been administered with the Spinal Cord Independence Measure scale (SCIM) (Catz, Itzkovich, Agranov, Ring, & Tamir, 1997) and the American Spinal Injury Association Impairment Scale (ASIA) (American Spinal Injury Association, 2008; see Table 2 for scores for each patient). The SCIM measures the ability of patients to perform basic daily living activities independently. The score can go from 0 to 100: the higher the score, the higher the level of independence of the patient. The ASIA allows to determine the severity of the neurological injury, in other words, if some sensory and motor functions are preserved. Its score ranges from A (no motor nor sensory function preserved) to E (normal sensation and motor function). For instance, a lesion level of D5 with an ASIA score of A means that below the fifth dorsal vertebra of the spinal cord, including the sacral area, there is no spared sensory or motor function. On the other hand, a lesion level of D5 with an ASIA score of C would mean that some motor functions are preserved below the level of injury.

Prior to the experiment, we measured the actual reaching range for each participant. This space has been defined as the longest distance at which the participant could place a cup on a table in front of him/her. More in detail, participants, seated at a distance of 25 cm from the table, were asked to place as far as possible a cup handled with their dominant hand for three times. The last cup placement has been taken as final measure, to control for muscles stretching. The distance between the participant's torso and the cup has been measured with a paper measuring tape to the nearest half centimetre. The participants' actual reaching range was collected to scale their perceived reaching range, that is, the boundary of their peripersonal space (see Data analyses section).

To assess the participants' representation of their peripersonal space, we adopted a modified version of the paradigm developed by Costantini et al., 2010. In each trial, participants viewed a 3D coloured image (1,024 9 768 pixels, corresponding to approximately 24.3 9 18.7 degrees of visual angle) of a cup placed on a table in a room, with the handle oriented to the right-hand-side. The cup was placed at different viewing distances (12 viewing distances, from 40 to 84 cm, with increments of 4 cm) from the participant in a randomized order. The size of the cup in the image ranged accordingly from 100 9 123 to 57 9 65 pixels, corresponding to approximately 2.5 9 3.1 and 1.4 9 1.6 degrees of visual angle, respectively). Participants were instructed to judge whether they could reach or not the cup and to press the corresponding 'yes' or 'no' key on the keyboard. Hand of response was randomized across participants. A blank frame lasting 2,000 ms interleaved each trial (inter-trial interval). The maximum time allowed to respond was set at 3,500 ms (Fig. 1). The task was composed by 144 trials (i.e., 12 repetitions for each of the 12 viewing distances). Finally, after the experiment, participants were asked to verbally report at how many distances they thought the cup was placed. No range was given for the answer. This was carried out to verify that participants were not aware of the number of distinct viewing distances where the cup was placed, which could have allowed them to use an explicit strategy to provide the reachability judgements. No participant correctly guessed the number of distances used. Previous evidence using the same task (e.g., Costantini, Ambrosini, Sinigaglia, & Gallese, 2011) showed a high accuracy in the participants' explicit judgements of the metric distance at which the virtual objects were presented (see Ambrosini et al., 2012).

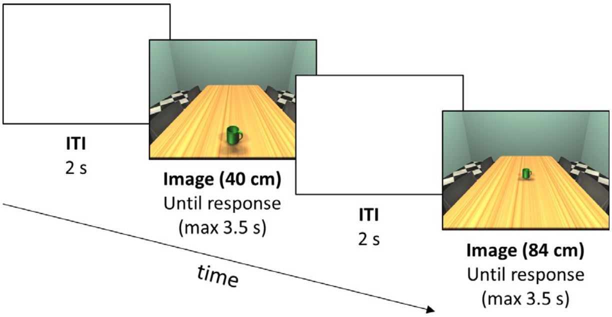

Figure 1. Schematic presentation of the experimental trials timeline. An example of a peripersonal (40 cm) and extrapersonal (84 cm) hypothetic trial is presented, even though it must be noted that in the real experiment, sequence of trials was randomized.

Stimuli have been presented on a laptop (16.3 inches screen). The computer was positioned at approximately 60 cm from the patient eyes. Answer buttons were letter 'a' and 'l' of the computer keyboard (European keyboard: these letters are placed at the extremity of the keyboard space). Screen luminosity was kept at maximum level for all participants. OpenSesame (Matho^t, Schreij, & Theeuwes, 2012) has been used to present the images and to collect accuracy and response time.

The neuropsychological screening and the experimental task have been administered in two different days of two consecutive weeks. Patients performed the experiment at the Unipolar Spinal Unit (ASST Grande Ospedale Metropolitano Niguarda, Milan, Italy) where they were hospitalized while the students were tested at Department of Brain and Behavioral Sciences, University of Pavia, Italy.

Data analyses

Demographic and neuropsychological measures of patients and controls have been compared by means of a two-tailed Fisher's exact test (gender) and two-tailed independent Student's t-tests (age, education and neuropsychological variables). Homo- geneity of variances was tested by the F-test, and, in case of heterogeneity, Welch's t-test was used.

Regarding the reachability judgements, for each participant, the boundary of the peripersonal space was estimated by fitting the dichotomic responses for the 12 distances with a psychometric function using_ a logistic regression model: $y = 1/ [1 + e—(a + bx)]$, where y is the proportion of participant's 'no' responses and x is the cup distance. The estimated parameters from the logistic model were used to determine the point of subjective equality (PSE, calculated as a/b), which indicates the estimated location of the boundary of the participant's peripersonal space and reflects the accuracy of the reachability judgement, and the so-called just-noticeable difference (JND, calculated as 1/b 9 log(.75/.25), which reflects the precision of the reachability judgement, that is, how neat or blurred is the transition between the participants' peri- and extrapersonal spaces. As that the actual reaching range (and therefore also the PSE) varied between participants, each participant's PSE was scaled by expressing it as the percentage deviation from his/her actual reaching range, with positive values indicating an overestimation. For statistical investigations, the scaled PSEs and JNDs were compared between patients and controls by carrying out two-tailed independent t- tests. Moreover, as the patient and the control groups were significantly different in terms of educations years and phonemic fluency (see Results and Table 1), and given that it was not possible to perfectly match them for the remaining demographic and neuropsychological confounding variables (Table 1), we carried out a series of analyses of covariance (ANCOVA) to confirm our results of prime interest, that is, the between- group effects, while ruling out possible confounding effects of demographic and neuropsychological variables in modulating it. We also assessed whether the variability in the patients' performance at the reachability judgement task was related to their clinical condition. We performed a series of correlational analysis between the accuracy and precision of patients' reachability judgements (i.e., their PSE and JND values, respectively) and their SCIM and ASIA scores, as well as the number of days passed from the injury to the neuropsychological screening (the ASIA scores were recoded: A = 3, B = 2, C = 1). We first computed both standard Pearson's and Spearman's rank correlations. Moreover, to control for the possible biases due to the presence of outliers, we also computed Pearson's and Spearman's skipped correlations (Wilcox, 2005) using the Robust Correlation toolbox (Pernet, Wilcox, & Rousselet, 2013; see Ambrosini & Vallesi, 2016, for details of the analysis and a discussion of the advantages of this approach). We conducted null hypothesis statistical significance testing using a nonparametric percentile bootstrap test (10,000 resamples; two-sided 95% confidence intervals (B-CI95%), corresponding to an alpha level of 0.05). The results of each correlational analysis were then Bonferroni-corrected for multiple comparisons ($n = 6$).

Finally, we analysed participants' response times (RTs). In this case, trials in which participants failed to respond (0.93%) were excluded from the analysis and raw RTs were log-transformed to improve normality. For each participant, the distances of presentation were recoded as a function of that participant's perceived reaching range (i.e., his/her PSE). We thus obtained a variable coding for the PSE-scaled distance of presentation of the mug (Distance predictor), which was calculated as the difference between the 12 original distances and each participant's PSE, and a factor coding for the space of presentation of the mug in relation to each participants' PSE (Space factor: peripersonal vs. extrapersonal). As the PSE-scaled distances were different across participants, we assessed the effects of the experimental manipulations on the RTs using a linear mixed-effect model as implemented by the function lmer from the lme4 library (Bates, Maechler, Bolker, & Walker, 2015) in R (version 2.15.2; R Core Team, 2014). We determined the simplest best (final) linear mixed-effect model to fit participants' RTs using log-likelihood ratio test (for a detailed description of the procedure, see Montefinese, Zannino, & Ambrosini, 2015; see also Ambrosini, Pezzulo & Costantini, 2015) according to standard procedures (e.g., Baayen, Davidson, & Bates, 2008; Quen´e & van den Bergh 2008). The final model included the fixed effects for all the independent variables of interest, that is, the Group factor (controls vs. SCI patients, coded as a [0,1] dummy variable), the space factor (extrapersonal vs. peripersonal, coded as a [0,1] dummy variable; see above), the PSE-scaled distance continuous predictor (see above), and the two- and three-way interactions between them. The statistical significance of these fixed effects was assessed by means of Markov Chain Monte Carlo (MCMC) sampling (10,000 samples) supported by the pvals.fnc function of the language R package (version 1.4; Baayen et al. 2008). We report the estimated coefficient (b), standard error (SE), and t values for each parameter included in the final model, as well as the p values (pMCMC) and upper and lower highest posterior density intervals (HPD95%) estimated on the basis of the posterior distribution of the corresponding parameters obtained through MCMC sampling.

Results

Demographic features

Patients and controls did not show significant differences concerning age and gender ($p = .227$ and $.640$, respectively, see Table 1). However, the analysis revealed that controls had a significantly higher level of education as compared to SCI patients ($p < .001$, see Table 1).

Neuropsychological parameters

Scores at the neuropsychological tests have been corrected for age and education following normative values of each test (see Task and procedure section for individual references). Comparing corrected scores between patients and controls, we found no differences concerning the MMSE, the Semantic Fluency Test, the Attentional

Matrices, and the FAB (all ps $> .05$, see Table 1). However, a significant difference emerged between groups at the Phonemic Fluency Test ($p = .006$, see Table 1).

Number of reported distances and actual reaching range

Patients estimate on average 5.2 distances ($SD = 1.69$) presented in the experiment, while controls 5.95 ($SD = 2.65$). No significant differences emerged between groups in this estimates ($t28 = .81$, $p = .423$, $d = 0.326$).

The actual reaching range was significantly different between groups ($t28 = 2.22$, $p = .035$, $d = 0.891$) with patients having, on average, an actual reaching range of 59.7 ($SD = 7.24$) cm and controls of 54.1 ($SD = 6.08$) cm.

Accuracy of reachability judgements

A two-tailed independent-sample t-test on the accuracy of the reachability judgements did not reveal any significant difference between groups concerning the scaled PSE ($t28 = 1.70$, $p = .100$, $d = 0.68$), although the same effect was only barely non-significant ($p = .0501$) when tested with a one-tailed t-test. However, a two-tailed one-sample t-test against 0 revealed that the controls significantly overestimated their reaching range ($M = 20.53\%$, $SD = 17.45\%$, $t19 = 5.26$, $p < .001$, $d = 1.18$), while the SCI patients did not show any significant bias ($M = 8.83\%$, $SD = 16.18\%$, $t9 = 1.73$, $p = .118$, $d = 0.55$).[1]

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[1] A sensitivity power analysis revealed that, for both groups, there was a sufficiently high power (1 b ≥ .80) to find a significant overestimation effect with a Cohen's d effect size of 1 that, albeit large, is comparable to those showed in various previous studies (d = 1.29, Ambrosini et al., 2012; d = 1.36, Costantini, Ambrosini, Sinigaglia, et al., 2011; d = .99, Mark et al., 1997). Therefore, our non-significant finding for the patient group could not be attributed to an a-priori lack of power: had patients showed the same effect as controls, in terms of its magnitude, we definitely had the power to reveal its significance.

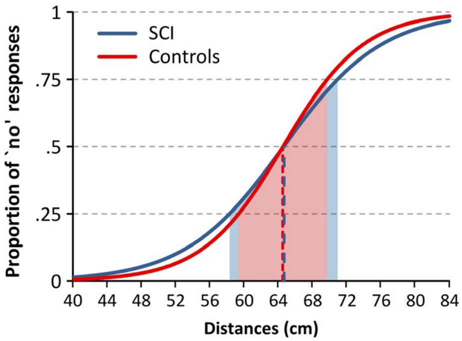

Figure 2. Psychometric functions describing reachability judgements as a function of the group. Psychometric functions are fitted to data averaged across participants in the SCI (blue solid line) and controls groups (red solid line). The average judgement rate across participants in each group was calculated for each distance value, and logistic functions were fitted to the averaged rates. The distance value at which each curve crosses the 0.5 line is the PSE for each group, which is indicated by the blue and red dashed lines for the SCI and controls, respectively. The light blue and light red shaded regions indicate the extent of the corresponding PSE JND region (see 'Data analysis' section).

Precision of reachability judgements

The analysis on the precision of the reachability judgements revealed that SCI patients showed significantly higher JND values (M = 4.01 cm, SD = 1.73 cm) as compared to controls (M = 2.79 cm, SD = 1.11 cm, t28 = 2.36, p = .025, d = 0.95). In other words, SCI patients had a more blurred boundary between peripersonal and extrapersonal spaces as compared to controls. Figure 2 shows the psychometric functions aggregated across participants in the SCI (blue lines) and the control (red lines) groups.

The significant Group effect on JND values was confirmed by the ANCOVA including all the demographic and neuropsychological covariates (F1,21 = 7.47, p = .012, g2 = .26). The significant Group effect on JND values was also confirmed by all the subsequent follow-up ANCOVAs including the same covariates one at a time (all F1,27 ≥ 4.41, all ps ≤ .045, all g2 ≥ .14) except the one including the FAB score, in which the Group effect was not significant (F1,27 = 3.33, p = .079, g2 = .11) (see Supporting Information, Tables S1 and S2).

Correlational analyses

The results of the correlational analyses revealed a significant correlation between the patients' SCIM scores and their JND values (Pearson's r = .774, B- CI95% = 0.934 to 0.521; p = .0006; Spearman's q = .787, B-CI95% = 0.997 to 0.236; p = .0061; note that no bivariate outliers were detected, so the robust correlations were the same as the standard ones). Therefore, patients' with greater disability were those who gave reachability judgements with less precision (or with higher variability) and, thus, had a more blurred boundary between peripersonal and extrapersonal spaces.

The robust Pearson's correlation between the patients' SCIM scores and their actual reaching range was also significant (r = —.552, B-CI95% = —0.903 to —0.096; p = .014), but this result was not confirmed by both the robust Spearman's (q = —.443, B-

Table 3. Estimated parameters and statistics of linear mixed-effects modelling of response times

Fixed effects	b	SE	t	lowHPD95%	upHPD95%	pMCMC
(Intercept)	6.8682	.0450	152.74	6.7888	6.9489	.0001
Group(SCI)	–0.0495	.0779	–0.64	–0.1857	0.0860	.4662
Space(PPS)	–0.0490	.0221	–0.22	–0.0908	–0.0054	.0290
Distance	–0.0177	.0012	–14.89	–0.0201	–0.0154	.0001
Group:Space	0.1153	.0380	3.03	0.0406	0.1899	.0020
Group:Distance	0.0049	.0020	2.43	0.0007	0.0087	.0172
Space:Distance	0.0338	.0014	23.38	0.0311	0.0368	.0001
Group:Space:Distance	–0.0050	.0025	–2.04	–0.0100	–0.0003	.0426

Note. b = estimated coefficient for each parameter in the model; SE = standard error; lowHPD95% and upHPD95% = lower and upper bounds of the estimated 95% highest posterior density intervals; pMCMC = Markov Chain Monte Carlo p value.

CI95% = – –0.897 to – – 0.317; p = .10) and the standard correlational analyses (Pearson's r = .295, B-CI95% = 0.798 to 0.274; p = .2938; Spearman's q = .196, B- CI95% = 0.789 to 0.459; p = .55), nor it survived the Bonferroni's correction for multiple comparisons; this result, thus, was likely biased by the distribution of the data, and, therefore, it will be not discussed further. The other correlations were not significant at either the standard or the robust correlational analyses.

Response times

The results of the linear mixed-effects analysis on the log-transformed RTs are shown in Table 3. The analysis revealed the significance of all the main effects except that of the

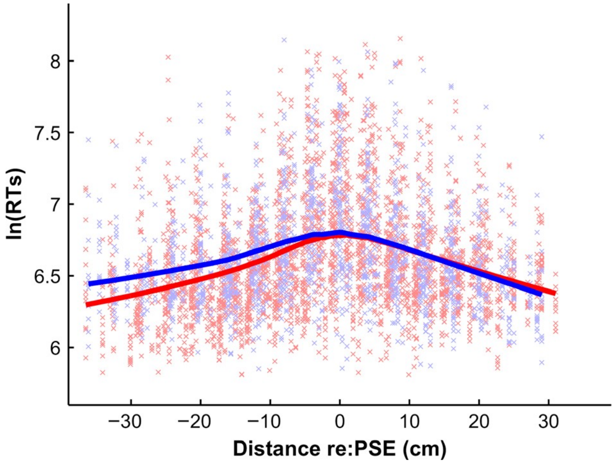

Figure 3. Response times (RTs) results. The figure shows the log-transformed RTs of SCI and controls participants (blue and red crosses, respectively) in all trials as a function of the PSE-scaled distance of presentation of the mug (abscissa; see 'Data analysis' section for details). Negative and positive distance values indicate, respectively, participants' peripersonal and extrapersonal spaces. For illustrative purpose, the solid lines show the corresponding locally weighted linear fit (Lowess, f = 0.75; Cleveland, 1979) for SCI and controls RTs (blue and red line, respectively

Group factor. Moreover, all the interactions were significant (Table 3). Of particular, interest for our hypothesis is the significant three-way interaction (b = .005, pMCMC = .043). This effect showed that the linear decrease in the RTs as the distance of the mug presented in the peripersonal space decreased was more pronounced for the controls as compared to the SCI patients. In other words, the controls were faster than SCI patients in giving their reachability judgements only when the mug was presented in the peripersonal space, and this differential effect became stronger as the distance of the mug became closer to the participant (see Figure 3).

Discussion

The representation of peripersonal space and, in particular, the relationship between an observer's representation of his/her body and action abilities and the environment is characterized by his/her ability to detect properties of objects relevant to actions and to internally represent them. As an example, through this skill, one can observe a cup and immediately 'implicitly know' if it graspable or not. This concept has been defined as "micro-affordances" (Faber, van Elk, & Jonas, 2016; Freeman, Itthipuripat, & Aron, 2016; Lemaitre, Heller, Navolio, & Zu´nigaPenaranda, 2015; Tucker & Ellis, 2004). Approximately 25% of rehabilitated patients with spinal cord injuries do not become independent ambulators (Wirz et al., 2005). Even in the absence of a structural brain damage, the interruption of the corticospinal tract can affect the transformation of contextual information into task-specific locomotion commands (Davidoff et al., 1992). As such, affordances play a relevant role in the case of SCI.

However, virtually nothing is known about how much a lesion to the spinal cord can affect peripersonal space representation and affordance perception.

To shed light on this issue, we enrolled 10 patients with paraplegia and 20 matched controls exploring whether individuals with paraplegia estimate the extent of their peripersonal space prompted by a graspable object in the same way as non-injured individuals do. We used a task that allows measuring the accuracy and precision of affordances-related reachability judgements for images of graspable objects located in peripersonal or extrapersonal space (adapted from the paradigm developed by Costantini et al. 2010). We predicted that, even when the ability to move the hands is spared as in the case of paraplegia, individuals who are prevented from exploring space in a canonical way would present a different profile, similarly to what has been found for body representation (Fiori et al., 2013; Fuentes et al., 2013).

Our results show three main findings. Firstly, despite the patients and non-injured individuals groups not showing any significant difference concerning the level of accuracy in estimating the location of their peripersonal space boundaries,[2] when considering them singly, only non-injured individuals show the typical overestimation of their reaching range, while patients do not. To date, a large number of studies have shown that we normally overestimate the reaching range of our arms – and, thus, the extent of our

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[2] The likely reason for the non-significance of the between-groups difference in scaled PSE values is that, despite the non-negligible effect size of this difference (indeed, controls showed a mean scaled

PSE that was more than twice the one showed by SCI patients, with a medium–large standardized effect size of d = 0.68; see Results), the between-subjects analysis we performed was not sufficiently powered to detect its significance. It is important here to note that a Bayesian two-sample t-test showed that there was no evidence in favour of the null hypothesis of the equality of patients' and controls' scaled PSE values (scaled-information Bayes factor in favour of the null = 0.722; Rouder, Speckman, Sun, Morey, & Iverson, 2009). Future studies using a higher number of SCI patients are thus needed to verify the significance or non-significance of this effect.

peripersonal space – that is, we generally tend to perceive that we can reach objects that are out of grasp (Ambrosini et al., 2012). In line with the idea that determining whether a visual object is reachable or not – or whether it falls within peripersonal space or not – is essentially a function of the observer's representations of his/her body and action abilities, two explanations have been proposed for the overestimation bias in perceived reachability. Both explanations are based on the observer's misconception of his/her own action abilities in performing the motor simulation involved in the reachability estimates. According to the whole-body engagement hypothesis (Rochat & Wraga, 1997), such an overestimation would originate from our everyday sensory–motor experience of reaching, which naturally requires multiple skeletal degrees of freedom, whereas the reaching range is generally tested in situations that prevent natural body movements and require only one degree of freedom (i.e., the extension of the arm without any other movements such as trunk flexion or hip rotation). According to the postural stability hypothesis (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989), we would naturally tend to operate in a 'risky' setting of our postural system, in which our reaching range is overestimated as long as the projected centre of mass of our body is safely supported during the simulated movements. Despite to date, neither hypotheses can account for the full pattern of results observed in the literature (Delevoye-Turrell et al., 2010; Fischer, 2000), both accounts are in line with our finding of a lack of overestimation biases in SCI patients. Indeed, SCI patients cannot engage in natural reaching movements involving the same number of musculoskeletal degrees of freedom as non-injured individuals, nor they can operate in a ‘risky’ postural setting and have to be more cautious about losing postural stability. This finding is in agreement with studies on healthy individuals using different types of locomotion, that is using a wheelchair, in which results show that postural changes indeed impact on affordances perception (Yasuda et al., 2014; Yu & Stoffregen, 2012; Yu et al., 2010).

Secondly, patients who took part in our study show a significantly higher variability in their reachability judgements (in other words, greater values of the JND parameter) than non-injured individuals. Put it differently, they are less precise and have a blurred boundary between peripersonal and extrapersonal space. Importantly, this finding is independent from the demographic and neuropsychological features of patients, with the only relevant exception of the score at the FAB, and was modulated by patients’ ability to perform everyday activities such as feeding and self-care, as assessed by the SCIM scale. Patients’ with greater disability, in other words lower scores at the SCIM, were less precise in providing reachability judgements or, in other words, the boundary between their peripersonal and extrapersonal space was more blurred. Notably, this association is not seen for ASIA scores, suggesting that experience and performing activities rather than spared/impaired functions play a role for affordances perception. This result confirms our hypothesis that SCI patients have a different representation of peripersonal space: the modification of their motor abilities and, in particular, their everyday experience of the inability to naturally engage in reaching movements modified the way they represent and experience peripersonal space, causing a blurring of the reaching range.

Related to this idea, a recent study has highlighted the importance of motor abilities in shaping peripersonal space (Scandola, Aglioti, Bonente, Avesani, & Moro, 2016). The authors investigate the perception of reachability in control participants and professional fencers, who, contrarily to untrained individuals and, especially, SCI patients, are well- trained to exert their reaching-related motor abilities and to experience their reaching range. The results showed that fencers had a low variability in their reachability judgements and, thus, a very sharp boundary of their peripersonal space, especially when asked to simulate reaching movements using the fencing sword as compared to a similar hand-held object for which they did not have extended motor experience.

Finally, our data highlight that patients are not faster in making their judgements on reachability in peripersonal space, while non-injured individuals are. Research has shown that 'yes' responses are usually faster than 'no' responses. Such difference in RTs is thought to reflect the uncertainty about the presence of the target perceptual feature when it is actually absent. The same applies in reachability judgements. The closer the object, the lesser the uncertainty. Interestingly, our patients did not show such a difference, suggesting that they are not sure of what is reachable.

Taken together, our results suggest that there is an impact of movement loss on affordances even when the upper limbs are not compromised. In other words, even though an individual is able to use his hands, the very fact of not being able to move and use their whole body to interact with the environment does impact his decoding of action- related space representation and objects' properties.

Our findings are in line with previous results that suggest an altered mental representation of the world in SCI patients. Previous studies have demonstrated that this impairment affects the body image (Fuentes et al., 2013), especially in terms of an overestimation of the length of the torso and the inferior limbs, and the body schema (Fiori et al., 2013), as shown by altered motor imagery abilities, that is the ability to imagine one's body part from different visual angles. Interestingly, this impairment does not depend on the lesion level. Our data further expand this knowledge suggesting that body and spatial representation is impacted by spinal lesions. In fact, patients show high variability and blurred boundaries for peripersonal space.

Our and previous findings can be explained in the light of an altered motor simulation in patients, resulting from the absence of movement, in other words due to the loss of on line action experience. It is known that experience modulates affordances perception; in particular each person, based on his/her motor experience, can simulate actions, taking advantage of this process thanks not to perceptual salience but mostly because of motor competences (Pezzulo, Barca, Bocconi, & Borghi, 2010). However, past experience does not seem to be enough to retain these abilities. Our patients were able to move before the lesion, but lost this ability for several months. Apparently, the lack of continuous motor performance cancels the ability to make use of motor-related perceptual features. This significant impairment occurring already in the subacute phase of SCI suggests that body representation relies on the continuous sensory motor updating rather than on a specific motor memory. Recent studies have shown that using a wheelchair can modify the boundaries of peripersonal space even in nonlesioned subjects (Galli, Noel, Canzoneri, Blanke, & Serino, 2015). Importantly, only when the use of a wheelchair is passive (i.e., somebody else is driving the wheelchair), the boundaries of peripersonal space seem to be enlarged (Galli et al., 2015). Thus, one could suppose that active use of wheelchair remaps peripersonal space even in SCI. However, our patients do not show an alteration in this direction. Possibly, a lesion that compromises sensory and motor afferences does slow the spatial remapping, even when a few months of training on a wheelchair are performed. Put it differently, motor simulation is efficient only if it is accompanied by a real motor act, and the use of a tool is not sufficient to rebalance the system. This finding is also in line with the concept of a body matrix (Moseley, Gallace, & Spence, 2012) integrating body and space. Future studies could explore in SCI patients directly the body matrix, to understand whether also this component of body representation is compro- mised after a spinal lesion.

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