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Listening to and mimicking respiration: Understanding and synchronizing joint actions

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Several studies provided evidence about the mutual influence between respiration and performance: breathing influences and is in turn influenced both by motor (Raßler & Kohl, 2000) and mental processes (Wientjes, Grossman, & Gaillard, 1998). Field experiences suggest that participants engaged in joint performances requiring a high degree of synchronization tend to breathe together to manage precise temporal coordination. This paper presents two studies aimed to explore if breathing sounds convey information about the activity being performed and to describe interpersonal breathing coordination during a joint action. In Study 1, 180 participants listened to ecological tracks of breathing sounds related to six activities different in degree of mental and physical effort in two conditions: listening vs. imitation. Most demanding activities were identified the most. Imitation significantly improved identification accuracy. Study 2 was aimed to develop a multilayer analysis to relate partners' respiratory behaviour during joint actions and to describe their respiratory and acoustic features. Audio recording of breathing sounds of a dyad was taken during a baseline and a joint obstacle course, both video-recorded. Respiratory, acoustic, and coordination indices were extracted and related to six action units. The multilayer analysis provided quantitative measurements of respiratory behaviour that enable descriptions and comparisons between conditions and actions.

Key words: breathing sounds, joint action, imitation, acoustic analyses

The relation between action and respiration has received broad attention in the field of sport psychology since several psycho-physiological studies provided evidences about the mutual influences between respiration and performance management: breathing appears to be entrained to synchronous motor processes and to influence in return both rhythm and precision of simultaneous actions (Raßler, 2000; Raßler & Kohl, 1996, 2000). The degree of coordination between movement and respiration is affected by several factors such as movement rate (Bechbache & Duffin, 1977; Bonsignore, Morici, Abate, Romano, & Bonsignore, 1998; Ebert, Raßler, & Hefter, 2000; Jasinskas, Wilson, & Hoare, 1980) and work rate (Bernasconi & Kohl 1993; Jasinskas et al., 1980; Raßler & Kohl, 1996): generally, higher movement rates and load levels enhance entrainment (Loring, Mead, & Waggener, 1990). Other studies have focused on the influence of mental tasks on respiration, describing in particular the effects of focused attention (Mador & Tobin, 1991; Wientjes, Grossman, & Gaillard, 1998), reaction tasks (Boiten, 1998), and arithmetic and logical tasks (Grossman & Wientjes, 2001; Vlemincx, Taelman, De Peuter, Van Diest, & Van Den Bergh, 2011). Results provide evidences that mental tasks influenced respiration in different ways. Experimental tasks however were not so definite as to allow the identification of the effects of discrete mental functions on respiration. Moreover, it's hard to isolate the impact of the emotional responses elicited by the tasks on the resulting breathing patterns.

While many studies have dealt with individual sport performances providing useful information on how to develop respiration trainings aimed at enhancing endurance, strength, precision, and concentration in athletic performance, less attention has been brought to the study of respiration in synchronized joint actions. If respiration actually provides useful cues about action timing and physical and mental effort, breathing together could be an effective way to improve atunement and synchronization between agents, in particular in team sports that require a high degree of synchronization. Performers engaged in highly synchronized activities like rowing, dancing, or playing music are often trained to rely on breathing sounds as a signal to coordinate reciprocal actions but there is poor scientific literature about

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the efficacy. However, some studies addressed issues related to this topic and underlined some interesting effects. First, respiration uniquely bridges the autonomic and the voluntary nervous system and can be consciously managed to influence your own physiological arousal. In particular, some studies suggested that mimicking emotional breathing patterns induces correspondent emotional feelings (Philippot, Chapelle, & Blairy, 2002). Secondly, there are evidences that synchronized movement improves perceptual sensitivity to the motion of the partner by increasing both attention and adaptation toward his movements (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007; Sabenz, Bekkering, & Knoblich, 2006; Schmidt & O'Brien, 1997; Valdesolo, Ouyang, & DeSteno, 2010) and that it enhances the sense of interpersonal similarity resulting in a better interpersonal coordination (Valdesolo et al., 2010). These studies encourage further investigations about the effects of breathing synchronization on interpersonal coordination.

We argue that breathing during joint actions could serve two different functions: first, a *perceptual-informative function,* since breathing sounds could become a signal to rely on in order to improve coordination. To reach this purpose, agents have to pay attention to each other's breathing to infer cues about the action being performed by the respective partner or the one the partner is about to start. This highlights first of all the need of studying respiratory behaviour not only in physiological terms but also in perceptual ones to describe what could be inferred from the features of the breathing sounds participants listen to. Secondly, a *synchronization function* could be involved, concerning the reciprocal synchronization of respiratory behaviour to support movement coordination. Respiration both influences and is influenced by simultaneous actions (Raßler, 2000; Raßler & Kohl, 1996, 2000) so it's possible that by increasing breathing synchronization agents can improve interpersonal coordination as has already been described regarding other motor activities (Sabenz et al., 2006; Valdesolo et al., 2010). From this perspective the investigation of the use of respiration during joint actions should be based on a set of acoustic indices allowing the description of breathing behaviour throughout the performance flow.

The present contribution provides the results of two studies aiming to analyze breathing behaviour during joint performances. Concerning the informative function of breathing, we aimed to investigate whether breathing sounds actually convey reliable cues about the degree of mental and physical efforts involved in a performance or even allow the identification of specific activity being performed. The synchronization function was examined considering first of all whether breathing synchronization enhances the ability to infer such information. From a methodological perspective it was then considered whether it could be possible to describe how breathing features vary during the action flow in relation to interpersonal coordination, considering the actions performed and the partner's respiratory behaviour.

STUDY 1

Study 1 was set with two aims. First one was to investigate what breathing sounds could convey about a person's activity. In particular, we investigated whether it was possible to identify the specific activity performed or to infer general dimensions, especially the degree of mental concentration and physical effort, which the previous studies have proved to affect respiration (Denot-Ledunois, Vardon, Perruchet, & Gallego, 1998; Loring et al., 1990; Shea, 1996). The second was to test whether the synchronization with breathing sound patterns enhances identification accuracy compared to mere listening.

Method

Sample. There were 179 psychology students (89.5% women) enrolled in an introduction psychology course who took part in the study. The experiment was presented as a non-mandatory workshop about the relation between breathing and well-being. They didn't receive any course credit for their participation in the study.

Experimental stimuli. Ecological tracks of breathing sounds related to six activities performed by different persons (two women, four men) served as experimental stimuli. Activities differed in the degree (low, medium, high) of mental concentration and physical effort. Considering tasks and factors that have been proven to influence respiration in previous literature, the level of physical effort was assigned based on movement and work rate characterizing each activity (Jasinskas et al., 1980; Raßler & Kohl, 1996). The degree of mental concentration was based on the level of attention and logical reasoning required (Grossman & Wientjes, 2001). Target activities were: (a) jogging, i.e., running at a steady pace – high physical effort (aerobic), low mental concentration; (b) stretching, i.e., a hamstring stretching exercise that requires one to sit on the floor with both legs out straight and to extend forward the arms as far as possible, holding the position for 30 seconds – high physical effort (anaerobic), low mental concentration; (c) obstacle course, i.e., walking along an obstacle course, climbing over some steps and avoiding some obstacles while carrying on a tray a container filled with water – medium physical effort, medium mental concentration; (d) Shanghai, a game consisting in picking sticks up with a hand from a circular jumble without moving the others – low physical effort, medium mental concentration; (e) logical task, i.e., solving a logical problem chosen among university selection tests – low physical effort, high mental concentration; and (f) resting, i.e., sitting quietly on a chair – low physical effort, low mental concentration. At the end of each task, the six participants were asked to rate the degree of mental and physical effort experienced while performing the activity on a 3-point Likert scale. Scores were consistent with the levels previously assigned.

All original tracks were recorded in ecological conditions using a Presonus Firestudio Project audio interface and a Shure WH30 XLR head microphone. Twenty seconds were extracted from each track to serve as experimental stimuli.

Self-report. After each task, participants had to fill in a questionnaire requiring them to: (a) rate the degree of physical effort and mental concentration concerning the performed activity on a 7-point Likert scale (0 [*none*] to 7 [*very intense*]); (b) choose among multiple choices the activity the breather was engaged in – the labels available included in random order the actual activities and six misleading ones (distracters), one for each track: resting–sleeping, logical task–reading, Shanghai–drawing, obstacle course–housework, jogging–step, and stretching–weight lifting; and (c) fill in a task evaluation form, at the end of the entire questionnaire, that required them to rate on a 7-point Likert scale (0 [*not at all*] to 7 [*a lot*]) the following aspects of the task: difficulty ("Difficult, since I have never done that before"), usefulness ("Useful to empathize with him"), discomfort ("Annoying, because it wasn't my spontaneous breathing"), involvement ("Involving, because I felt physically activated"), and mechanics ("I did it just because I had been required to" – only in the imitation condition).

Procedure. There were 89 participants randomly chosen that took part in the listening condition, and 90 in the imitation condition. Both instructions and audio tracks were presented on a computer screen through a PowerPoint slide presentation to allow auto-administration. The volume of all PC stations was set at the maximum level. Participants used personal earphones and were provided with a paper-and-pencil version of the questionnaire. In listening condition participants had to listen to each track three times, then fill in the corresponding page of the questionnaire. In imitation condition they did the same thing but, before filling in the questionnaire, they were asked to mimic that breathing pattern for at least 20 seconds. Both groups were given 45 minutes to complete the task.

Analyses. One of the most frequent measures of identification accuracy is the proportion of correctly identified target stimuli. However, this method confuses recognition accuracy with the tendency to choose a particular multiple choice category more than others (response bias). *Unbiased hit rate* (H_u; Wagner, 1993) allows the correction of the response bias and takes into account the amount of choices participants are provided with. It is calculated by multiplying the hit rate for that label (the number of accurate uses of the label, divided by the number of times that label was presented) by the differential accuracy (the number of accurate uses of the label, divided by the total number of uses of that label). Therefore, H_u were extracted for each subject as a measure of identification accuracy. Since H_u is a proportion, arcsine transformation was calculated to allow statistical analysis. Values ranged from 0 to 1.57 (perfect score).

Results

Task rating form. First, the validity of the task was assessed. To this aim, we first calculated means and standard deviations for each item of the task rating form in both conditions. Global results suggest that the task was considered quite difficult *(M* = 4.33, *SD* = 1.55) and average involving *(M* = 3.66, *SD* = 1.60) but not too annoying (*M* = 2.54, *SD* = 1.61) nor mechanical (*M* = 2.70, *SD* = 1.66). Both listening and mimicking condition were evaluated useful for participants to empathize with the breather (*M* = 4.79, *SD* = 1.57). Independent samples *t*-tests were conducted to compare items scores in listening and mimicking condition. The results indicate that the mimicking task (*M* = 3.99, *SD* = 1.70) was considered significantly easier than the listening one (*M* = 4.67, *SD* = 1.30, $t(177) = 2.989$, $p < .01$), and also more annoying (listening condition: *M* = 1.86, *SD* = 1.30; mimicking condition: *M* = 3.20, *SD* = 1.62; $t(177) = -6.022$, $p < .001$). No differences emerged concerning involvement and usefulness.

Identification accuracy. First, H_u were computed per judge for each stimulus separately. Values ranged from 0 to 1 (perfect score). Table 1 shows means and standard deviations for each activity, in the two different conditions.

Identification rates were generally low (*M* = 0.27). A two-way analysis of variance (ANOVA; 2*6 with repeat-

Table 1
Descriptive statistics of activities' unbiased hit rates (H_u)

	H_u					
	Listening		Mimicking		Total	
Target activities	*M*	*SD*	*M*	*SD*	*M*	*SD*
Jogging	0.70	0.44	0.83	0.34	0.76	0.40
Stretching	0.18	0.37	0.34	0.47	0.26	0.43
Logical task	0.22	0.40	0.27	0.45	0.25	0.43
Resting	0.16	0.35	0.17	0.35	0.16	0.35
Shanghai	0.05	0.21	0.16	0.37	0.10	0.30
Obstacle course	0.02	0.11	0.10	0.30	0.06	0.23

Table 2
Identification accuracy – percentage of labels chosen for each activity

	Target activity											
Given labels	Resting		Logical task		Shanghai		Obstacle course		Jogging		Stretching	
	LC	MC	LC	MC	LC	MC	LC	MC	LC	MC	LC	MC
Resting	19.10	20.22	3.37	4.49	5.62	10.11	8.99	14.61[a]	1.12	0.00	4.49	5.62
Sleeping	30.34[a]	26.97	8.99	6.74	38.20[a]	29.21[a]	12.36	5.62	2.25	0.00	5.62	3.37
Logical task	6.74	6.74	24.72	28.09	5.62	8.99	10.11	3.37	0.00	0.00	8.99	3.37
Reading	25.84	38.20[a]	8.99	12.36	5.62	3.37	7.87	14.61[a]	0.00	0.00	1.12	0.00
Shanghai	1.12	0.00	22.47	22.47	5.62	16.85	4.49	2.25	0.00	0.00	2.25	0.00
Drawing	7.87	1.12	24.72[a]	23.60[a]	7.87	12.36	2.25	5.62	0.00	0.00	0.00	1.12
Obstacle course	1.12	0.00	0.00	0.00	2.25	1.12	2.25	10.11	7.87	3.37	2.25	0.00
Housework	0.00	1.12	1.12	0.00	4.49	2.25	1.12	11.24	2.25	0.00	0.00	5.62
Jogging	0.00	0.00	0.00	0.00	2.25	4.49	8.99	2.25	74.16[a]	87.64[a]	2.25	4.49
Step	0.00	0.00	0.00	0.00	1.12	1.12	4.49	4.49	5.62	6.74	2.25	1.12
Stretching	4.49	1.12	2.25	1.12	10.11	5.62	14.61	12.36	4.49	1.12	21.35	33.71
Weight lifting	1.12	0.00	1.12	1.12	7.87	3.37	19.10[a]	12.36	1.12	1.12	46.07[a]	38.20[a]

Note. LC = listening condition; MC = mimicking condition.
[a] These values highlight the main confusions for each target activity in both conditions.

ed measures on last factor) was run with activity (jogging, stretching, obstacle course, Shanghai, logical task, and resting) as a within-subject factor, condition (listening and mimicking) as a between-subject factor, and arcsine transformed H_u score per judge as a dependent variable. The analysis showed highly significant main effects for activity, *F*(5, 880) = 92.213, *p* < .001, and condition, *F*(1, 176) = 13.048, *p* < .001, but not for their interaction. These findings first suggest that some breathing patterns were better recognized than others, in particular jogging, followed by logical task and stretching. Moreover, they indicate that imitation significantly improves the ability to identify activities, apart from resting.

Confusion matrix on raw hit rates of participants' responses was drawn in order to underline systematic confusion between activities. Table 2 provides the percentages of choice of each given label, represented by different rows, for each target activity. Jogging was sometimes confused with obstacle course in the listening condition, and with its paired alternative, step, in the imitation condition. Stretching was principally targeted with its paired alternative, weight lifting. Logical task was often confused with Shanghai and drawing, both low activation activities having comparable levels of mental concentration. Resting was mainly associated with sleeping in the listening condition, which was its paired alternative, and reading, which involves much more mental concentration, in the imitation condition. Shanghai and obstacle course came out as the most often confused, in particular, the former with sleeping, the latter both with low demanding physical activities, such as sleeping, and with high demanding ones, such as weight lifting.

Mental concentration and physical effort. Table 3 shows mean rates of mental concentration and physical effort assigned in the listening and in the mimicking condition. To analyze mean scores of perceived mental concentration and physical effort, two distinct two-way ANOVAs (2*6 with repeated measures on last factor) were conducted with activity (jogging, stretching, obstacle course, Shanghai, logical task, and resting) as a within-subject factor and condition (listening and mimicking) as a between-subject factor. Both analyses yielded only a significant main effect for activity, while no significant differences emerged between conditions nor for their interaction. As far as mental concentration scores are concerned (*F*(5, 880) = 25.122, *p* < .001), post hoc contrast analyses pointed out logical task as the most demanding activity (vs. resting: *F*(1, 177) = 73.650, *p* < .001; vs. Shanghai: *F*(1, 177) = 75.290, *p* < .001; vs. obstacle course: *F*(1, 177) = 64.927, *p* < .001; vs. jogging: *F*(1, 177) = 94.977, *p* < .001; vs. stretching: *F*(1, 177) = 60.678, *p* < .001), while no differences emerged between the other levels. Considering physical effort (*F*(5, 880) = 310.465, *p* < .001), mean score were consistent with the actual degree of physical effort required by each activity. Contrast analyses revealed significant differences between all activities. In particular, jogging was considered the most demanding one (vs. resting: *F*(1, 177) = 1878.880, *p* < .001; vs. logical task: *F*(1, 177) = 1325.02, *p* < .001; vs. Shanghai: *F*(1, 177) = 656.631, *p* < .001; vs. obstacle course: *F*(1, 177) = 305.038, *p* < .001; vs. stretching: *F*(1, 177) = 74.715, *p* < .001) and resting the least demanding (vs. logical task: *F*(1, 177) = 32.249, *p* < .001; vs. Shanghai: *F*(1, 177) = 53.379, *p* < .001; vs. obstacle course: *F*(1, 177) = 175.812, *p* < .001; vs. stretching: *F*(1, 177) = 549.643, *p* < .001; vs. jogging: *F*(1, 177) = 1878.880, *p* < .001).

Table 3
Average ratings of mental concentration and physical effort in listening and mimicking condition

	Mental concentration						Physical effort					
	Listening		Mimicking		Total		Listening		Mimicking		Total	
Target activities	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Resting	3.07	1.76	3.43	2.03	3.25	1.91	1.52	1.15	1.35	0.77	1.44	0.98
Logical task	4.58	1.76	4.91	1.63	4.75	1.71	2.06	1.08	2.03	1.19	2.05	1.13
Shanghai	2.93	1.76	3.57	1.95	3.25	1.88	2.65	1.79	2.36	1.75	2.51	1.77
Obstacle course	3.55	1.58	3.44	1.54	3.49	1.56	3.58	1.95	3.33	1.83	3.45	1.89
Stretching	3.43	1.61	3.38	1.62	3.40	1.61	5.05	1.79	5.07	1.69	5.06	1.74
Jogging	3.29	1.57	3.13	1.59	3.21	1.57	6.18	1.03	6.26	1.08	6.22	1.05

Discussion

The analysis of the answers to the task ratings form allowed verifying the validity of the experimental procedure. The task was rated as just slightly annoying and mechanical, while it reached higher rates of involvement and difficulty. It is not surprising that difficulty reached quite high ratings, the task being highly unusual to the participants in the study. Anyway, ratings were not too high, thus these results confirm the adequacy of the experimental procedure. The imitation task was perceived as significantly easier compared to the listening one but also more annoying. Discomfort could be related to the request to adopt a way of breathing that wasn't natural to the mimickers, while the reported effortlessness is more surprising, also considering that both conditions were rated as equally useful in improving identification. Probably the imitation task was experienced as more involving and gave a higher sense of control compared to passive listening.

Activity decoding. One of the principal aims of this first study was to explore the perceptual informative function of the breathing sound. Based on the results, the main finding is that breathing sounds generally convey more reliable information about the degree of physical effort exerted, but poor cues about the specific kind of activity performed. Identification rates (H_u) were generally low and statistically significant differences emerged between activities independently from experimental conditions. In particular, highly demanding physical activities (jogging and stretching) were better identified compared to low demanding ones. This could depend on the fact that they were the most familiar stimuli, involving louder breathing: it's easier in everyday life to hear this kind of sounds related to fatiguing actions. Moreover, people are often taught how to breathe to better perform such activities. They also represent more common situation compared to obstacle course and Shanghai that were the most confused: Shanghai mainly with other low demanding activities, and obstacle course with both high and low demanding activities. This label was probably intended as high hurdles performance, which is actually a much more effortful action. Resting is characterized by the slowest breathing rhythm and by softer sounds compared to other conditions; thus, it could be easily related to low arousing situations. Finally, logical task has been more poorly identified than high demanding activities since it is quite unlikely that breathing can be audible during mental performance, compared to physical ones: in this kind of task it's more difficult to rely on the informative function of breathing. Confusion analysis showed that target activities were often confused with their paired alternatives, i.e., activities characterized by comparable levels of mental concentration and physical effort. This suggests, as mentioned before, that breathing sounds provide more reliable information about such dimensions compared to the kind of the activity performed.

Physical effort and mental concentration ratings. Analysis confirmed the ability to discern between activities requiring different degree of physical effort and mental concentration. Physical effort, in particular, turned to be more recognizable than mental effort. In fact, while participants were able to point out logical task as the most demanding activity, they were not able to draw clear distinctions between the others. Besides, physical effort appeared more discriminative: participants were able to correctly range the experimental stimuli from the less demanding (resting) to the most (jogging/stretching). Activities requiring the highest physical effort were also better identified compared to those requiring low and intermediate physical effort, having, as previously discussed, a more evident influence on breathing sounds features. Moreover, participants were able to discriminate between aerobic and anaerobic effort: jogging was mostly confused with step and stretching with weight lifting, but confusion didn't occur between those terms. These results could be interpreted also in the light of previous studies that have described breathing entrainment to synchronous motor processes, remarking that the higher the movement and the work rate, the stronger the entrainment (Bechbache & Duffin, 1977; Bernasconi & Kohl 1993; Bonsignore et al., 1998; Jasinskas et al., 1980; Raßler & Kohl, 1996). Since respiration is more entrained to effortful actions, it is likely that acoustic features of breathing patterns effectively reflect those levels of energy, in particular through changes in rhythm and intensity (jogging and stretching audio tracks were actually characterized by the longest cycle durations and the highest inspiration and expiration intensity). As far as logical task is concerned, previous literature suggests that focused attention tends to induce fast, shallow, and regular breathing and an increase of sigh rate (Grossman & Wientjes, 2001; Vlemincx et al., 2011). The logical task breathing pattern was characterized by the presence of both a clear sigh and a breath holding at the beginning of the track followed by shallow and regular breathing, which participants could have related to the mental performance. A deeper examination is needed; these preliminary results so far suggest that breathing sounds could be informative about some general dimensions of the activities performed, particularly when they require high levels of mental and physical effort.

Imitation vs. listening. A second aim of this study was to investigate one aspect of the synchronization function we assumed, in particular whether breathing synchronization enhances identification accuracy compared to mere listening. Results show that mimicry, which implies breathing synchronization, significantly improves identification of all activities apart from resting. These results are in line with the hypothesis that imitation of postures, vocal, and facial expression and, as far as this study is regarded, breathing pattern could trigger experiences similar to those felt by the mimicked person (Hatfield, Cacioppo, & Rapson, 1992; Hess, Kappas, McHugo, Lanzetta, & Kleck, 1992). Respiration being strictly related to body–mind experience, it's likely that breathing manipulation induces physiological states similar to those of the mimicked activity, inducing closer identification. Future research should consider additional physiological measurements to provide higher control of the actual autonomic activation of participants when mimicking the different breathing patterns. Another hypothesis is that the mimicry conditions arouse deeper concentration on the stimuli in order to reproduce them better. As a consequence, identification accuracy increased. Besides, participants didn't rate differently the degree of mental concentration and physical effort in the two experimental conditions. Thus, imitation didn't improve the identification of the degree of mental and physical load required by the different activities. These findings could suggest two things: first, it is likely that these general dimensions, in particular physical effort, were easier to rate through acoustic cues, while accurate identification of the specific activity required an additional effort. These results are consistent with previous literature on synchronized movement (Richardson et al., 2007; Sabenz et al., 2006; Valdesolo et al., 2010) and suggest that breathing together improves attention toward the partner's behaviours and is considered useful to enhance the sense of interpersonal similarity (see task rating form). Further research could then investigate in more depth whether these aspects are useful in improving interpersonal coordination. To do that, it will be important to examine agent's actions and breathing behaviour throughout the performance flow, which is the focus of Study 2. Secondly, since imitation facilitated identification of individual activity but not of degree of mental and physical load, it is likely that imitation focused participants' attention on some acoustic features that supported more subtle discriminations independent from those general dimensions. For example, both logical task and Shanghai breathing patterns were characterized by the presence of a sigh, generally more frequent in tasks requiring focused attention (Grossman & Wientjes, 2001; Vlemincx et al., 2011), but the latter was also associated with faster and more irregular respiration, suggesting the several picking up movements of the subject. Obstacle course pattern sounded instead like a quite irregular sequence of accented breaths of variable intensity that suggested changes in the subject's walking rhythm and in the effort exerted. Further investigations could compare different activities characterized by a similar degree of mental and physical effort to test this hypothesis, relying on a set of indices that allow a more accurate acoustic analysis of the associated breathing patterns.

Limitations. These findings suggest that people can gather reliable cues about the degree of physical effort exerted by an agent by listening to breathing sounds, and that this ability improves with imitation. On the other hand, breathing sounds seem to convey generally poor cues about the kind of activities performed, when these are not characterized by high levels of physical effort or mental concentration. It is likely that participants were not used to rely on this kind of expressive signal, and this explanation would be consistent with the difficulty assessments in the task rating form results. Moreover, audio tracks lasted only 20 seconds: it would be interesting to see whether a longer period would facilitate identification accuracy and, more in detail, how much time is generally required to recognize the target activity. Having collected breathing samples in ecological conditions, we relied on stimuli with ambiguous expressive features. Employment of ecological stimuli has the advantage of using breathing sounds that are not artificially reproduced, being instead collected in natural settings. However, it has the disadvantage of preventing any rigorous control and standardization of some important variables such as the context where each breathing track was produced and, as far as emotional tracks are concerned, the actual intensity of subject's feelings. This experimental choice could have led to the generation of unclear stimuli that could have influenced the identification accuracy. Finally, no generalization is allowed about the acoustic features of breathing pattern related to a specific activity: a wider sample of breathing patterns should be collected for each performance condition.

Once gone beyond these limitations, future research could investigate whether breathing patterns could be intentionally used to convey cues about the activity performed, thus supporting coordination between partners during a joint performance. It could also investigate how much the ability to closely reproduce a breathing pattern is related to higher identification accuracy.

STUDY 2

Study 1 investigated the informative power of breathing sounds and whether breathing imitation and synchronization improve the ability to infer such information. Study 2 aimed to: (a) develop a valid procedure that allows the description of how breathing features vary throughout the performance flow with relation to interpersonal coordination, and (b) define a set of indices to describe respiratory behaviour through acoustic measurements, linking them to the actions performed by the performers.

Method

Sample. Four men (mean age: 34 years) recruited among the university staff voluntarily took part in the study. They didn't know each other and they casually paired in two couples.

Apparatus. Four audio tracks of breathing sounds were recorded using a Presonus Firestudio Project computer recording system and two Shure WH30 XLR head microphones. All experimental conditions were video-taped using a Canon Legria HF200 camera (HD).

Procedure. Audio recording of breathing sounds was taken during a resting situation (baseline) and a joint obstacle course. They were not allowed to speak during the tasks. In the baseline situation, participants just sat on a chair breathing normally for 120 seconds. In the joint obstacle course situation participants had to hold a tray with their hands, standing face to face to each other, and carrying seven containers filled with water across an obstacle course spilling as little water as possible. To increase the need to manage close interpersonal coordination, some obstacles were set along the course. Participants crossed the course only once: they had first to climb over a step, then to lay the tray down on the floor, to pick it up again and to perform backwards the same course. They had no time limitation, and the two couples took on average 154 seconds (*SD* = 37) to complete the task.

Analyses

Audio analyses. Each audio track was screened using the acoustic analysis software Praat. Starting and ending time (in milliseconds) of each respiratory event, which was defined as single expiration and inspiration, were manually detected using three reference frames: (a) the waveform representation of the audio track, (b) its synchronous spectrographic representation (view range: 0-8.000 Hz; window length: 0.03 s), and (c) the corresponding audio signal. A total sample of 580 respiratory events was collected, spread as following: 199 breaths at baseline and 381 in joint obstacle course. To capture the association between behavioural demands and breathing changes, we needed to build set of indices that allow a *multilayer analysis* of respiratory behaviour through multiple respiratory measures. In order to achieve this goal, we argued that three classes of indices should be derived from breathing sounds analysis: *respiratory indices*, *acoustic indices*, and *coordination indices.*

Respiratory indices. They include conventional measurements of ventilation related to temporal features of the respiratory signal, in particular: respiratory rate, cycle duration, inspiratory time, expiratory time, inspiratory/expiratory time ratio, respiratory pauses time, inspiratory pauses time, and number of apnoeas. Mean and standard deviation were estimated for each index. To define which pauses should be considered as apnoeas, three criteria have been adopted: (a) pauses duration should be longer than *M* + 2 *SD*; (b) a break occurred within the same inspiration/expiration event; and (c) pause, although with duration shorter than *M* + 2 *SD*, was followed by a glottal noise, signalling previous interruption of the respiratory cycle.

A*coustic indices*. They describe breathing sounds features, in particular: inspiration intensity, expiration intensity, envelope amplitude of breathing sound tracks, inspiration spectral centroid, expiration spectral centroid, and number of accented breaths. Mean, standard deviation, and range were estimated for each index. Spectral centroid is an indicator of perceived sharpness of a sound and describes whether the spectral content of a signal is dominated by high or low frequencies. It is calculated as the weighted mean of the frequencies present in the signal, determined using a Fourier transform, where their magnitudes are the weights:

$$Centroid = \frac{\sum_{n=0}^{N-1} f(n)x(n)}{\sum_{n=0}^{N-1} x(n)}$$

where x(n) represents the weighted frequency value, or magnitude, of bin number n, and f(n) represents the central frequency of that bin. The number of accented breaths was estimated since breathing sounds were sometimes characterized by several amplitude peaks; these “accents” were related to the kind of action performed. As an example, while running or walking, the movement of our body is reflected in corresponding accents in breathing sounds.

Coordination indices. They allow linking the respiratory behaviours of both agents during the joint performance, in particular: lag between couple of closest breaths' onsets, number of breaths within 0-100 ms per total amount of breaths, number of breaths within 100-250 ms per total amount of breaths, number of breaths within 250-500 ms per total amount of breaths, and number of breaths longer than 500 ms per total amount of breaths. Synchronism could be assessed on the basis of *prefixed thresholds* or *relative measurements.* Prefixed thresholds require defining a fixed interval on the basis of the event's timing. Relative measurements provide estimates of the actual time lag between two events without using any threshold. The former allow categorizing events on a range of classes, providing a more sensitive description of the changes occurring along the stream of the action. On the other hand, we were not able to find in literature reliable thresholds for respiratory synchrony with relation to joint actions. We then chose to estimate mean, standard deviation, and range of the lag between couple of closest breaths' onset as relative measurement. Thresholds were set considering previous psychophysical studies about auditory perception and conscious motor control. As far as auditory perception is considered, two breathing events could be considered as concurrent on the basis of human ability to perceive two sounds as distinct: (a) to hear two separate events and not a single one, two sounds must be at least 50 ms apart from the onset of two consecutive events (Steudel, 1933); (b) two auditory events are integrated in a bound unit when they occur at an intervening interval of 50 and 100 ms (Yabe et al., 1998); (c) above 100 ms human hearing begins to discern rhythmic shapes and groups (Roederer, 1995); and (d) 250 ms periodicity is the fastest rate at which a man can discern a beat or pulse (Westergaard, 1975). However, while engaged in a joint action, people presumably do not breathe with the purpose to be heard by the partner, rather in order to manage the performance. Thus, not only human perception threshold should be considered, but also the temporal interval needed to consciously control an action—500 ms (Libet, 2004). In order to take into consideration both auditory perception and conscious motor control, we thus hypothesized three consecutive thresholds of synchrony considering the duration of the lag: 0-100 ms (above which two acoustic events are rhythmically distinguished), 100-250 ms (above which we can clearly discern a beat), and 250-500 ms (which is the threshold for conscious control of an action), and coupled breaths' lag longer than 500 ms was defined as non-simultaneous breath. Occurrence of breaths falling within each temporal category was assessed.

Video analyses. To relate changes in breathing behaviours to particular action units, video recordings were analyzed, and six main action classes were identified and previous indices were coded within each category: (a) lifting the tray from the table, (b) walking, (c) stepping over a step, (d) laying the tray down on the floor, (e) picking up the tray from the floor, and (f) placing the tray on the table. Finally, amplitude envelope of both breathing tracks was extracted and overlapped, allowing a more detailed analysis of how breath sound intensity changed across per-

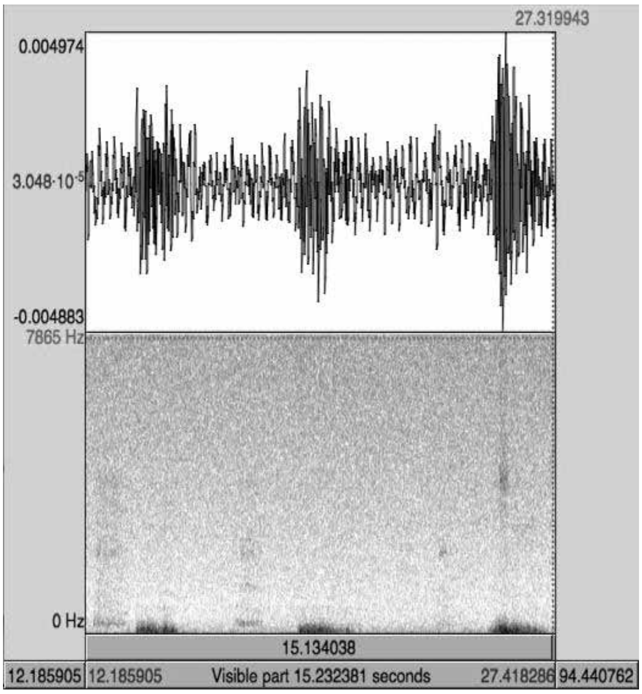

Figure 1. Extract of the breathing pattern during the baseline (duration: 15.232 s; window length: 0.03 s; view range: 0-8000 Hz).

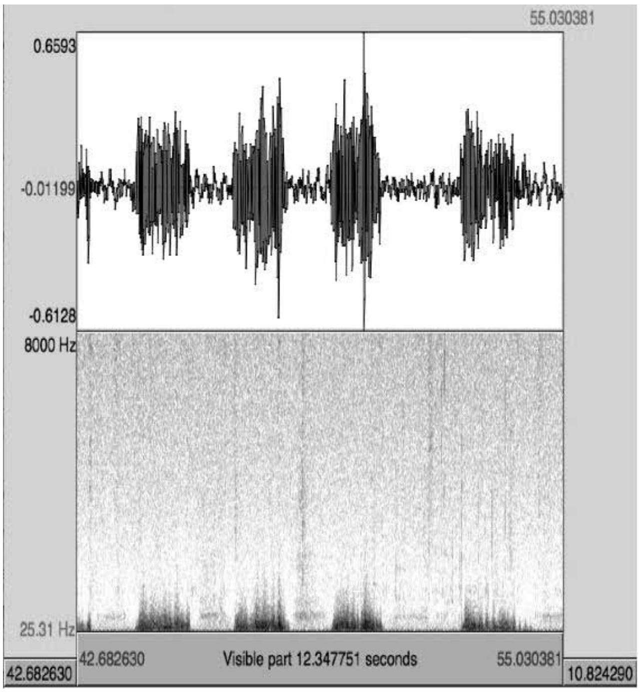

Figure 2. Extract of the breathing pattern during the obstacle course (duration: 12.347 s; window length: 0.03 s; view range: 0-8000 Hz).

formance, and highlighting the strongest moment of synchrony over time.

Results

Baseline vs. joint action. Table 4 shows the multilayer analysis results of the baseline and obstacle course conditions. Considering respiratory indices, respiratory rate and cycle duration were higher in the obstacle course compared to the baseline while pauses and expiratory time were shorter. As acoustic indices are regarded, the obstacle course condition produced sharper sounds compared to the baseline, both as inspiration and expiration are concerned, and more accented breaths that seem to follow the action rhythm. Figures 1 and 2 illustrate the differences between the two acoustic breathing patterns.

Finally, as far as coordination indices are concerned, baseline mean temporal lag between closest breaths was above 600 ms, while in the obstacle condition it was around 350 ms (Table 4). A χ^2 test underlines the significance of the higher amount of simultaneous breaths in the joint performance compared to baseline, $\chi^2(1, N = 94) = 6.128, p = .01$.

Relating breathing to action categories. Table 5 shows the multilayer analysis results of the main action categories considered (lifting, walking, step, laying down, and placing). Respiratory indices change across the different phases of the course: respiratory rate becomes higher in correspondence to the step obstacle as well as during the final placing of the tray on the table. Inspiratory/expiratory time ratio, as a result of changes in inspiratory and expiratory durations, differs over time too. Highest number of apnoeas occurred when participants laid down the tray on the floor and then lifted it again, corresponding to the highest physical effort. Considering acoustic indices, most effortful actions (step and laying down) were also characterized by the louder sounds and the higher amount of accented breath. Beside, sounds were softer when lifting and placing the tray on the table (the less effortful actions). Finally, spectral centroid was quite stable through time: inspirations became a bit sharper and variability increased only in the laying down phase. Coordination indices were also extracted. Mean synchronism appeared to be higher when laying the tray down on the floor and when posing it on the table. Analysis of simultaneous indices shows which category was prevalent in each phase: generally the prevailing was the 250-500 ms one with the exception of the last phase, where a lag between 100-250 ms was preeminent.

To analyze coordination between participants across time, first amplitude envelope of both breathing tracks was extracted and they were overlapped. The plot was then examined according to the different action phases (see example in Figure 3). This representation allowed a more detailed analysis of how breath sound intensity changes across dif-

Table 4
Multilayer analysis of respiratory behaviour in baseline and obstacle course conditions

Indices			Baseline	Obstacle course
Respiratory indices	Respiratory rate	*M* (*SD*)	11.92 (3.64)	18.23 (3.09)
	Cycle duration^a	*M* (*SD*)	2.757 (0.682)	2.284 (0.845)
	I time^a	*M* (*SD*)	1.184 (0.451)	0.873 (0.274)
	E time^a	*M* (*SD*)	1.555 (0.590)	1.268 (0.371)
	E/I ratio	*M* (*SD*)	1.408 (0.556)	1.738 (0.951)
	Pauses time^a	*M* (*SD*)	1.175 (0.956)	0.535 (0.883)
	N breath holding	*M* (*SD*)	1.75 (0.96)	4.00 (0.41)
Acoustic indices	E intensity^b	*M* (*SD*)	35.98 (2.67)	36.82 (4.96)
		range	11.23	19.30
	I intensity^b	*M* (*SD*)	32.90 (1.57)	31.24 (2.96)
		range	6.67	12.11
	E spectral centroid^c	*M* (*SD*)	420.29 (250.23)	483.10 (304.07)
	I spectral centroid^c	*M* (*SD*)	525.01 (337.91)	710.23 (304.07)
	N accented breaths	*M* (*SD*)	12.68 (2.15)	20.52 (5.09)
Coordination indices	Lag breaths onset	*M* (*SD*)	0.631 (0.522)	0.364 (0.311)
	Simultaneous index 0-100 ms^d	*M* (*SD*)	10.23 (4.33)	25.11 (17.24)
	Simultaneous index 100-250 ms^d	*M* (*SD*)	15.94 (7.79)	23.34 (6.78)
	Simultaneous index 250-500 ms^d	*M* (*SD*)	16.55 (7.51)	25.70 (0.99)
	Simultaneous index > 500 ms^d	*M* (*SD*)	57.29 (4.04)	25.76 (23.16)

Note. I = inspiration; E = expiration; N = number of.
^{a}Expressed in seconds. ^{b}Expressed in decibels. ^{c}Expressed in hertz. ^{d}Expressed in percent.

Table 5
Multilayer analysis of respiratory behaviour in the main action units

Indices			Action units				
			Lifting	Walking	Step	Laying down	Placing
Respiratory indices	Respiratory rate	*M* (*SD*)	12.00 (1.36)	17.26 (3.41)	20.80 (1.60)	14.90 (5.27)	19.34 (3.03)
	Cycle duration[a]	*M* (*SD*)	2.802 (0.709)	2.290 (0.827)	2.498 (0.386)	2.850 (1.138)	2.348 (0.415)
	I time[a]	*M* (*SD*)	1.229 (0.655)	0.987 (0.220)	0.873 (0.187)	1.161 (0.517)	1.086 (0.152)
	E time[a]	*M* (*SD*)	1.596 (1.515)	1.356 (0.332)	1.380 (0.280)	1.662 (1.003)	1.134 (0.380)
	E/I ratio	*M* (*SD*)	1.605 (0.155)	2.005 (1.069)	1.765 (0.580)	2.545 (2.140)	1.160 (0.520)
	Pauses time[a]	*M* (*SD*)	3.341 (1.370)	4.165 (3.414)	3.544 (1.596)	4.414 (2.627)	–
	N breath holding	*M* (*SD*)	0.50 (0.58)	0.31 (0.60)	0.50 (0.76)	1.50 (0.58)	–
Acoustic indices	E intensity[b]	*M* (*SD*)	33.74 (4.76)	34.34 (4.03)	36.42 (5.98)	36.89 (5.06)	33.23 (4.96)
		range	10.30	12.18	18.62	19.14	10.45
	I intensity[b]	*M* (*SD*)	29.47 (2.96)	31.24 (3.01)	30.03 (5.03)	32.16 (4.76)	29.78 (2.85)
		range	8.14	7.45	12.15	14.49	9.32
	E spectral centroid[c]	*M* (*SD*)	478.20 (303.07)	480.10 (310.34)	476.23 (337.12)	484.75 (333.11)	478.58 (304.34)
	I spectral centroid[c]	*M* (*SD*)	696.35 (376.04)	703.27 (355.41)	710.23 (314.07)	700.93 (398.67)	699.46 (303.93)
	N accented breaths	*M* (*SD*)	1.00 (0.00)	0.50 (0.63)	2.13 (1.96)	2.50 (0.58)	0.25 (0.50)
Coordination indices	Lag breaths onset	*M* (*SD*)	0.460 (0.224)	0.511 (0.379)	0.455 (0.343)	0.378 (0.195)	0.360 (0.264)
	Simultaneous index 0-100 ms[d]	*M* (*SD*)	9.93 (13.14)	15.01 (11.73)	9.94 (3.78)	14.51 (7.71)	15.46 (17.68)
	Simultaneous index 100-250 ms[d]	*M* (*SD*)	–	16.65 (20.58)	19.32 (17.47)	4.56 (6.43)	32.50 (10.61)
	Simultaneous index 250-500 ms[d]	*M* (*SD*)	69.38 (42.43)	23.61 (20.94)	39.01 (10.66)	43.64 (23.14)	22.54 (3.54)
	Simultaneous index > 500 ms[d]	*M* (*SD*)	20.69 (28.28)	44.73 (26.76)	31.73 (9.91)	37.28 (24.43)	29.50 (10.61)

Note. I = inspiration; E = expiration; N = number of.
[a]Expressed in seconds. [b]Expressed in decibels. [c]Expressed in hertz. [d]Expressed in percent.

ferent phases of the performance, and enabled us to find the moment where synchronism in breathing sounds onset appeared to be higher.

Discussion

The central issue of this second study was to develop a multilayer analysis that allows the description of how breathing features vary throughout the performance flow. To do that, a set of acoustic indices was derived and its descriptive power was tested, to examine whether it allows an effective description of respiratory and acoustic features of breathing considering both the actions performed and the partner's respiratory behaviour throughout the performance flow. We believe that this step was essential to address the question of how much respiration serves interpersonal coordination. The proposed multilayer analysis allowed both the assessment of some of the conventional measurements of ventilation as well as of some acoustic features of breathing sounds. Moreover, it allowed drawing relations between

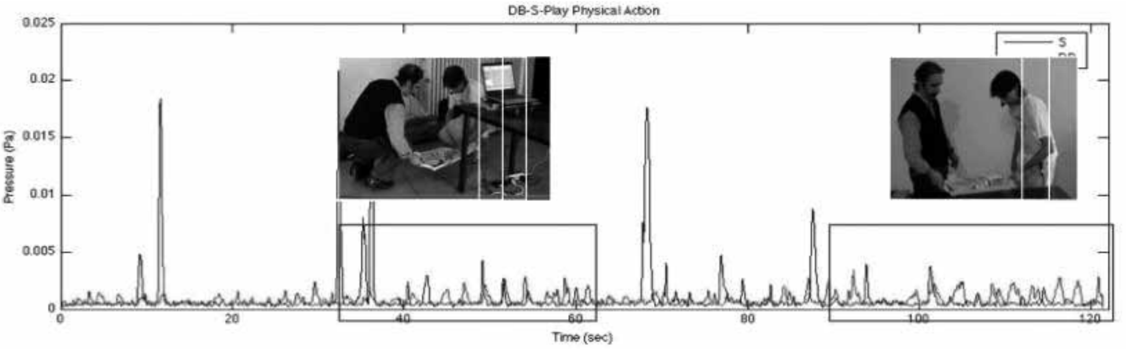

Figure 3. Overlap of amplitude envelope of two breath sound tracks related to different action phases.

respiratory sounds and the activity being performed. For example, breathing sounds were sharper during an activity compared to the baseline condition and most effortful moments were characterized by louder sounds, more accented breaths, and apnoeas. Coordination indices enabled to infer information about the relation between breathing behaviour and simultaneous performance, and between partners' breathing during joint performance. Mean synchronism were higher both when laying the tray down on the floor and when placing it on the table. Probably this depended on the fact that in these phases participants were performing the same action, which is not necessarily true for step (which requires one partner to climb over the step, when the other stands on the floor) and walking phases (which does not necessarily require walking in the same rhythm). Compared to lifting, which in contrast should be similar to placing and laying down, participants had more time to understand and reciprocally adapt their respective movements to better coordinate the action. Coordinated changes in action and respiratory rhythm are particularly evident while laying down the tray: this is the most delicate trial of the course and is characterized by both the slowest movements and the slowest respiratory rate.

Thus, although no generalization could be outlined based on the analyses only on two couples, it is possible that the stronger the need for synchronized movements between agents, the more synchronized their respiration. The entrainment of breathing rhythm to a voluntary movement seems to be an unconscious process (Bechbache & Duffin, 1977; Ebert et al., 2000; Jasinskas et al., 1980), therefore the increased respiratory synchrony between partners could be a natural outcome derived from the greater synchrony in their movements. If further studies should confirm that the agents' breathing behaviours become more synchronous in correspondence to more coordinate joint actions, they could be effective signals to rely on in support to joint action management. Then, it could be possible to address the question of whether breathing together purposely could improve interpersonal coordination. Since previous studies have shown that respiration influences temporal pattern and precision of voluntary movements (Raßler, 2000; Raßler & Kohl, 2000), it is likely that this effect could also be found in joint actions. The proposed analysis method could support further studies that would continue with more detailed video analyses deepening the investigation of whether participants' breathing together actually improves interpersonal coordination and degree of joint movement precision.

Limitations. As these comparisons were based on only two couples of participants, they don't allow any generalization of the results. Further studies should be carried on a broader sample to deepen the investigation of what these preliminary findings suggest. Moreover, broadening of the analysis levels, in particular the spectral indices set, could provide more detailed descriptions of breathing behaviour.

Conclusion. These two studies provide preliminary analyses of breathing behaviour during joint performances. Study 1 suggests that breathing sounds mainly convey information about the degree of physical and mental effort performed more than about the specific activity, although breathing synchronization improves identification accuracy. These findings suggest that athletes engaged in joint performances could, by increasing attention to their partners' breathing, continuously gather information about their physical state and increase their sensitivity to what they are experiencing. Secondly, Study 2 provides a multilayer analysis method that allows the description of how breathing features vary throughout the performance execution in relation to the actions performed and the agents' respiratory behaviour. Being a new field of research, further investigations are needed, both to confirm and to widen the discussed results. This approach could hopefully support further investigation about how and how much breathing together may improve interpersonal coordination in joint actions.

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