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I, Riley C Mayr, hereby submit this original work as part of the requirements for the degree of Master of Arts in Psychology.

It is entitled:

How Much for Joint Action?
Assessing the Cost of Working Together

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How Much for Joint Action?

Assessing the Cost of Working Together

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Abstract

Any action a person performs requires energy. One way to maximize the number of actions one can perform is to minimize the amount of energy necessary for each action. Every individual has their own most efficient movement frequency, and any movements deviating from that frequency, either above or below, lead to an increase in energy expenditure. This most efficient movement frequency is disrupted, though, when another person joins the action. When two people participate in joint action, they may need to leave their preferred movement frequencies to synchronize at a movement frequency in the middle of their two frequencies. This naturally leads to an increase in energy expenditure because they are moving outside their natural frequencies. However, when two people come together to perform an action, their energy expenditure oftentimes is reduced. For example, two actors who work together to move a heavy box split the load between the two of them, instead of taking on the full weight of the box alone. Load sharing leads to a lower individual energy expenditure for each person in the pair. The current study sought to quantify the energy expended during a task in different levels of joint action. I utilized a joint sawing task to create different levels of joint action and Expired Gas Analysis to measure each participant's energy expenditure during the joint sawing task at each level of joint action. Cross-Recurrence Quantification Analysis was used to measure the coordination between participants during the task. Energy expenditure was examined both by experimental condition and block presentation order to determine effects of experimental manipulation and motor learning. No effect of either condition or block presentation order was present in the energy expenditure data. Current findings do not support the idea that coordination does not impact energy expenditure in joint action.

Contents

1 INTRODUCTION

1.1 Joint Action

Oftentimes, performing a physical action with another person instead of doing it alone is advantageous. Whether that advantage is to reduce the amount of time it takes to complete the task or to conserve energy, working with a partner alleviates many struggles that come with working alone. Acting together to alter the environment is called joint action (Sebanz, Bekkering, & Knoblich, 2006).

Isenhower, Richardson, Carello, Baron, and Marsh (2010) showed that clear decision points exist based on the affordances of the actors and the object when people determine whether or not they can perform an action alone or prefer to interact with another person. They found that people reach a critical point, determined by their arm lengths and whether or not they can transport a long plank, and seek help when they perceive that they will have trouble completing the action alone. Although it might be intuitive that joint action emerges during a task that requires a physical interaction and load sharing, it was shown that providing haptic information to both actors creates a similar interaction in which one individual's action affects another person's action even in cases where no physical exchange takes place (Noy, Dekel, & Alon, 2011). Thus, joint action (here defined as the mutual influence of the agents on each other) also occurs when two people are working together on a task in which they have to coordinate in an overlapping workspace or in close vicinity (Lorenz, Vlaskamp, Kasparbauer, Mörtl, & Hirche, 2014; Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007; Schmidt & O'Brien, 1997). While agents clearly must coordinate in such cases in order to avoid colliding with each other, this problem would not necessarily occur if agents perform the same task in their own workspace. However, it was shown that joint action emerges as soon as agents start exchanging any sensory information while interacting with each other (Richardson et al., 2007; Schmidt & O'Brien, 1997; Schmidt, Richardson, Arsenault, & Galantucci, 2007). Because action coupling emerges frequently in joint action, one could speculate that there is also a benefit from engaging in this coupled interaction.

1.2 Levels of Jointness

An important characteristic of joint action is the mutual influence and adaptation to each other's actions, which is expressed in the actual sharing of the task with respect to achieving a certain goal and the adaptation or attunement to the respective other agent (Lorenz et al., 2014; Noy et al., 2011; Vesper, Soutschek, & Schubö, 2009). There are many different scenarios that joint action can occur in, and a distinction can be made between these different *jointness* levels: Single Action, Pseudo Joint Action, and Factual Joint Action.

1.2.1 Single Action

Single Action (SA) takes place in action scenarios that involve only one person, meaning it is an action that has zero *jointness*. SA includes any tasks that can be completed alone and do not require the help of another person according to the individuals own judgment (Isenhower, Richardson, Carello, Baron, & Marsh, 2010).

1.2.2 Pseudo Joint Action

Pseudo Joint Action (PJA) builds upon SA, in that task completion requires two or more people, but does not require individuals to adapt to each other. PJA scenarios happen frequently, most often when two people are working on the same task in non-overlapping workspaces, paying no attention to each other. An example of a PJA is a group of factory workers assembling toys on the line. They are all doing similar actions, accomplishing a task together, but no actor's actions reciprocally influence the actions of their fellow workers. Because of this addition of more agents to the group, the *jointness* of the task increases over SA. However, as the agents do not influence each other, it is not yet a task that is accomplished jointly. Thus, PJA is defined as an action that two agents perform at the same time, eventually even with the same goal in mind, but without mutual influence on each other's actions. PJAs look like a group of people performing single actions.

1.2.3 Factual Joint Action

Factual Joint Action (FJA) also requires two or more people working together to complete a task. Unlike PJA, FJA involves the agents working together directly, thereby influencing each other's actions. When two agents are physically coupled (e.g., when they carry a couch together), they share a physical connection and automatically influence each other's actions as long as that physical connection exists, and haptic information exchange can also occur. Non-mechanical coupling, however, exists when agents coordinate their actions through vision or audition instead of mechanical and haptic coupling. FJA, which can be defined as an interaction between two or more agents that is characterized by both agents' mutual influence on each other's individual actions, can occur in all of these various cases of coupling between the co-actors.

1.2.4 Emergent Coordination as Factual Joint Action

Coordination between two co-actors can emerge spontaneously under certain task constraints (Schmidt & O'Brien, 1997). Coordination becomes most apparent during joint action that places the co-actors in a scenario in which they are physically connected and the task success is wholly dependent on the coordination and cooperation of their actions, like moving a heavy object together. However, similar coordination emerges when co-actors are simply placed near each other when performing similar actions. For example, it was shown that visual information exchange can enhance this coupling (Schmidt et al., 2007). Likewise, the stronger the coupling between the actors, the more coordinated their actions will be (Schmidt & Richardson, 2008; Schmidt & Turvey, 1995). Because people readily fall into coordination in joint action, what advantage comes from this coordination? Are there physiological benefits, such as saving energy, that come from synchronous join action that drive coordination?

1.3 Energy Consumption and Metabolic Cost

Every action across the *jointness* spectrum requires expending energy to make these activities possible. One way to maximize the total work, or number of successive actions, a person can do is to minimize the overall cost of each action. Increasing the total amount of work a person can do can have a variety of positive effects ranging from a more consistent workflow rate (i.e., more steadily working instead of having to take breaks), to allowing the person to have a larger energy store in case of an emergency.

1.3.1 Energetic Costs During Joint Action

Unless otherwise constrained, when producing cyclical actions people tend to move at a preferred movement frequency (i.e., a resonant frequency) that is related to the biomechanical properties of their limbs, which represents an energetic optimum (Ralston, 1958; Turvey, Schmidt, Rosenblum, & Kugler, 1988). In some cases, though, when people act alone they tend to move faster than when they act with a partner to complete a task quicker, regardless of the energetic cost, consistent with the idea of temporal discounting (Shadmehr, 2010). Temporal discounting is the concept that states when people execute a faster movement, this will yield a larger reward (completing more of the task), disregarding the additional cost required for movement execution. Research has shown that although longer duration movements use less energy than shorter movements, people prefer not to move this way performing a reaching movement when acting alone (Berret & Jean, 2016) and sometimes there is even a higher metabolic cost for movements that are too slow (Huang, Kram, & Ahmed, 2012). All movement styles requiring people to move from their optimum movement frequency, present in joint action, result in an increase in energy expenditure.

Likewise, it was shown that during joint action both actors depart from their natural movement frequencies, moving towards each other to arrive at a compromise frequency (Noy et al., 2011). For example, in social relationships, when people are instructed to walk the same distance with a partner as opposed to walking it alone, they alter their movement frequency in order to accommodate their partner (Wagnild & Wall-Scheffler, 2013). In the context of energy consumption, this is striking, as it was also shown that if individuals deviate from their natural frequency by moving at an either higher or lower frequency, energy demands increase for that movements (Holt, Hamill, & Andres, 1991; Wagnild & Wall-Scheffler, 2013). If these two individuals walking together do not have the same resonant movement frequency, at least one of the actors must abandon their natural frequency to match that of their partner and thus potentially increase metabolic cost. Since during joint action, both partners usually leave their natural movement frequency to coordinate, energy expenditure of both partners can be assumed to increase. With this in mind, Meagher and Marsh (2013) found that when participants were asked to estimate how far they could carry a heavy object either alone or with a partner, the participants estimated the distance to be farther when they had help than when they were carrying it alone.

One interpretation of these results is that people think that a task is more difficult when having to work with someone else.

1.3.2 Energetic Benefits During Joint Action

The distinction between PJA and FJA is necessary because while many single actions can be performed as both PJA or FJA, the actions of people change as soon as people are able to pay attention to and get information from their partner. Although people alter their movements when working together, leaving their preferred movement frequencies and thus increasing their energetic cost (Alessandro, Delis, Nori, Panzeri, & Berret, 2013; Berret & Jean, 2016; Noy et al., 2011; Noy, Weiser, & Friedman, 2017; Vesper, van der Wel, Knoblich, & Sebanz, 2011), joint action still has benefits. Two actors coming together to perform an action allows them to do more together than they could otherwise do alone. Some actions are simply impossible for a single person to perform. Most people cannot carry a large couch by themselves, so they will often ask someone else’s help. By simply working together to carry the couch across the room, these two people have not only distributed the load making it easier to lift, but also stabilized the load by grabbing it in more places around the couch’s perimeter. As action costs energy, if agents are working together while lifting heavy objects, they can additionally save individual energy and/or can carry heavier loads than when trying to lift the object alone. Meagher and Marsh (2013) found that participants overestimated the distance to the goal position when they knew they would have help carrying the load. Another interpretation of this result is that participants believe they can do more when they know they will be sharing the load. This suggests that carrying the object together requires less energy on the individual level. Even though working with others can increase difficulty, the energetic benefits from sharing the load often outweigh the difficulties.

2 SUMMARY AND OBJECTIVES

In summary, people often engage in joint action in order to achieve more than possible at the individual level. When the joint task entails a rhythmic movement, the co-actors need to detune from their natural frequency and adapt to each other, which should come at an energetic cost. Although energy consumption has been measured during task performance in single actions like walking, running, and performing oscillatory horizontal arm movements (Esposti, Esposito, Cé, & Baldissera, 2010; Farris & Sawicki, 2012; Huang & Ahmed, 2012; Sims et al., 2018), a disagreement exists in the current literature on how joint action should change the energy expenditure of the co-actors. One argument is that any deviation away from an individual's natural frequency, like those that occur during synchronous movements of two people with differing limb lengths and masses, will automatically result in an increase of energy expenditure. The other is that working together on a task reduces the amount of energy required to perform the same action compared to when someone performs the action alone.

Therefore, the objective of the current project is to quantify energy consumption during human action at various jointness levels. In particular, the primary question is whether energy consumption is increased or reduced when two humans engage in FJA as opposed to PJA or single action, while always objectively performing the same activity.

2.1 Hypothesis

Two hypotheses were tested. First, when individuals acted in the level of Factual Joint Action, their individual energy expenditure would be different than acting in levels of Pseudo Joint Action and Single Action. Second, when individuals achieved synchronous coordination, their individual energy expenditure would be different than when they were not coordinated.

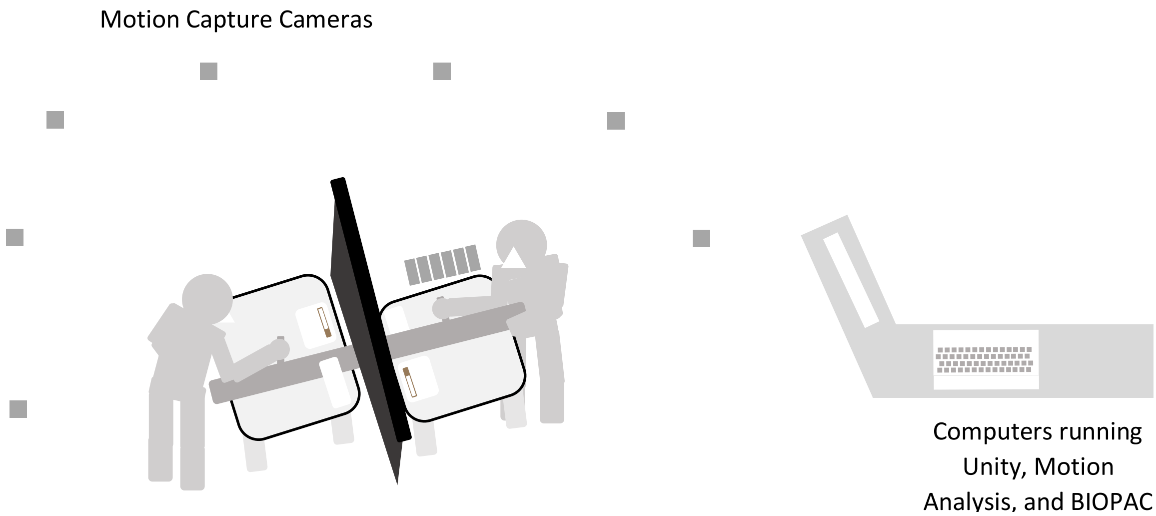

Figure 1. Schematic of entire setup, consisting of the different systems that are detailed below.

3 METHOD

3.1 Participants

20 undergraduate students from the University of Cincinnati were split into 10 pairs (mean age 24.1 years, 8 female) to participate in the current study. All participants reported right-hand dominance and no physical impairments that would prevent them from properly executing the instructed movements.

3.2 Task

In order to understand the differences in energy uses across different levels of joint activity, participants were asked to engage in a joint sawing task, simulating the actions performed by a dyad when using a two-person cross-cut saw. This task was chosen because it satisfied the necessary criteria, outlined below. It created a task space that allowed participants to synchronize, which is necessary to see if there are differences between the three defined joint action levels (no synchrony in SA and PJA, synchrony in FJA). The sawing task was also physically demanding, requiring participants to expend enough energy to register a change in the

BIOPAC expired gas analysis system. Lastly, the sawing task did not require the participants to move around, but allowed them to stand in one spot, a requirement for the expired gas analysis systems. A visual representation of the task setup can be found in Figure 1.

Throughout each trial, participants used the apparatus (see Section 3.4.1) to “saw” through the virtual log that appeared on a computer screen in front of them. The experimental apparatus allowed for physical, visual, and auditory isolation of participants from each other. The only chance participants had to exchange information was through visual and auditory information available during FJA trials. Participants were completely isolated in both SA and PJA trials.

Although the amount of information about their partner changed throughout the three conditions, their required work remained the same. Participants “sawed” through the same thickness “log” in every trial of the experiment, controlled by the amount of distance they moved the “saw” during each trial. This study sought to create three different levels of joint action (SA, PJA, FJA), manipulating the jointness of the task without changing the work required to complete each trial.

3.3 Design

The current study employed a within-subjects design with three jointness levels (SA, PJA, FJA).

3.4 Setup

In order to assess how the jointness level affected energy expenditure, three computer systems were combined and an apparatus with which participants physically engaged was

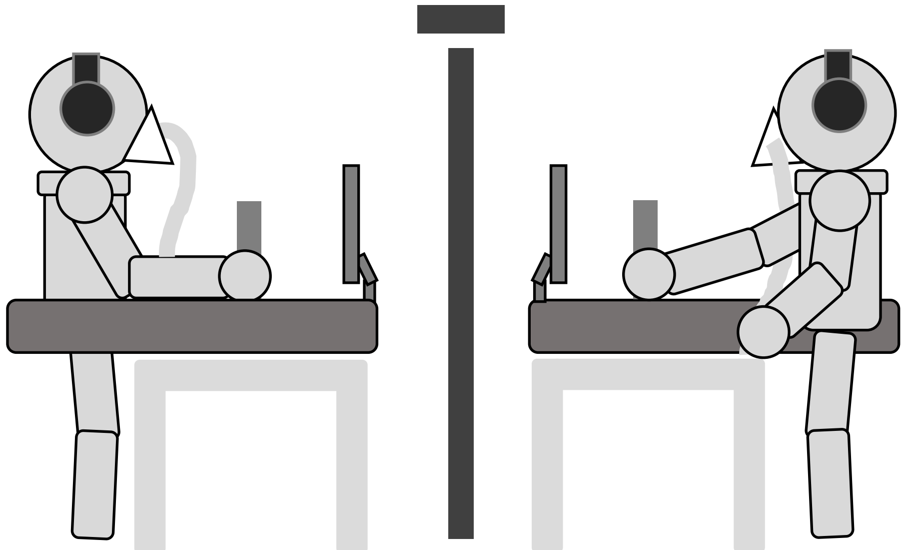

Figure 2. Experimental Setup, as seen during SA and PJA trials. Participants were visually occluded from each other with a blackout curtain and acoustically isolated by noise cancelling headphones playing white noise.

created. A BIOPAC expired gas analysis system was used to collect energy expenditure data. A 20-camera Motion Analysis Corporation Kestrel motion tracking system was used to collect movement data of each participant's saw position. A custom Unity program was used to guide participants with instructions and display their task progress during each trial throughout the experiment.

The experimental space consisted of two identical tables, placed across from each other, with a computer monitor and the experimental apparatus mounted to their top (See Figure 1). The 20-camera motion capture system surrounded the experiment space, ensuring good capture coverage. Participants were separated by a curtain (see Figure 2) and wore noise cancelling headphones playing white noise during the SA and PJA trials to provide the necessary isolation for the manipulation. The curtain and headphones were removed to allow participants to see and hear their partners during the FJA trials.

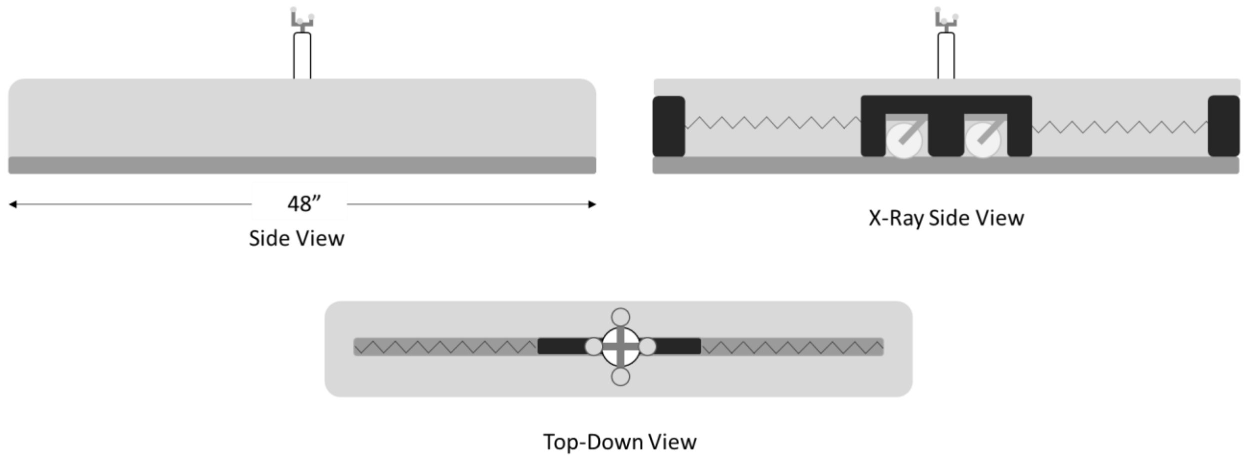

Figure 3. Schematic of experimental apparatus. One smaller block of wood was mounted to large, rubber casters to minimize rolling resistance. Opposing springs created resistance as participants moved the manipulator forward and backward in a sawing motion

3.4.1 Sawing Apparatus

An experimental apparatus was created to mimic the action of using a real two person cross-cut saw to cut the virtual logs (see Figure 3). The experimental apparatus consisted of 48" long frames constructed of 2" × 4" boards oriented vertically with a sled board that rolled on casters between them to hold the handle. To create a realistic resistance, mimicking that of sawing a real log, opposing extension springs were connected from the end of the frame to the sled board. The overall length of the apparatus was built from measurements of maximum forward and backward sawing distance of a 200cm tall colleague to ensure that any participant would be able to use the "saw" without any issues (smaller participants would not reach far enough to maximally extend the saw's reach). A mark was also indicated on the apparatus at 30cm forward from the saw's resting state (50% of the maximum forward movement travel), and participants were instructed to move to at least that mark to ensure participants moved enough to register a saw stroke. To enable true manipulations of both individual and joint actions, a second, exact copy of the described experimental apparatus was built so that one apparatus is available for each participant in the pair.

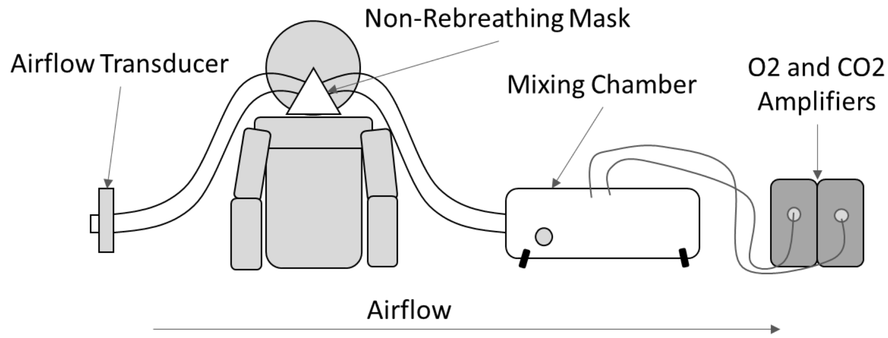

Figure 4. Schematic of airflow through components of Expired Gas Analysis System. Each participant breathed into their own Expired Gas Analysis system.

3.4.2 Energy Expenditure

Metabolic cost is the amount of energy expended when performing a task, measured in calories or joules (Lighton, 2008). One way to measure metabolic cost is by means of expired gas analysis, which measures the rate of a person's oxygen expulsion against their rate of carbon dioxide production during the performance of a task (Lighton, 2008). Comparing these values provides the necessary data to calculate the oxygen consumption during an action, which gives the values necessary to calculate metabolic cost.

Each participant was equipped with a respiration mask that was connected to an expired gas analysis system (BIOPAC Systems, Inc.; see Figure 4 for a schematic of this apparatus). Air flowed into the system through the airflow transducer, which measured the amount of air that passes through it in ml/s. As the connected participant inhaled, air passed in through the one-way intake valve of the facemask, entered the participant's body and was respired. Air then left the facemask through the one-way exit valve to the 5-liter mixing chamber. As the air condensed in the mixing chamber, it was pumped out by the O_2 and CO_2 amplifiers which read the percentage of the respective compounds in the air. The Respiratory Exchange Ratio (RER) is not measured directly but is the ratio of the volume of CO_2 production divided by the volume of O_2

consumption. To assess these volumes, first, the volume of inspired air in l/min is calculated by integrating the inspired airflow data over a 60 s interval. Then, this value is converted to standard pressure using a conversion function. After that, a Haldane Transformation is performed on the standardized value to find the volume of expired air per minute using the volume of inspired air, the concentration of CO_2 in the mixing chamber, and the concentration of O_2 in the mixing chamber (Wilmore & Costill, 1973). The volume of O_2 consumed per minute is then calculated by taking the volume of O_2 inspired and subtracting the volume of O_2 expired per minute. The same calculation is then performed to find CO_2 consumed, substituting CO_2 for O_2 in the previous calculation. Finally, the RER is calculated by dividing the CO_2 consumption by O_2 consumption. Since these calculations are performed continuously on every frame at 62.5Hz, this resulted in a timeseries for each of these described variables, including RER.

3.4.3 Motion Capture

Motion Tracking was utilized to capture the 3D position of the saw handles throughout the experiment at 60Hz. Using the 20 camera Kestrel Digital RealTime System from Motion Analysis and unique geometrical arrangements of passive, reflective markers on top of each saw handle, the handle of each participant was tracked, and each participants' sawing motions were recorded. The motion tracking system consists of 20 cameras spread around the perimeter of a large experiment room, each emitting infrared (IR) light. The IR light reflects off the passive markers and back into the cameras which feed the video information to a computer running the recording and processing software Cortex (Motion Analysis Inc.). Cortex then triangulates the

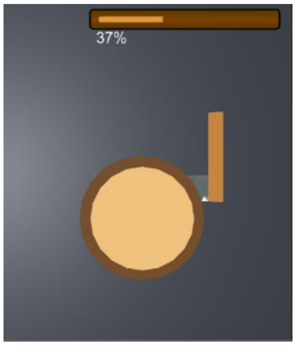

Figure 5a. Informational Display Screen During Single Action Conditions. Each participant saw their own log, saw, and progress bar. Saw dropped vertically down the log to indicate task progress

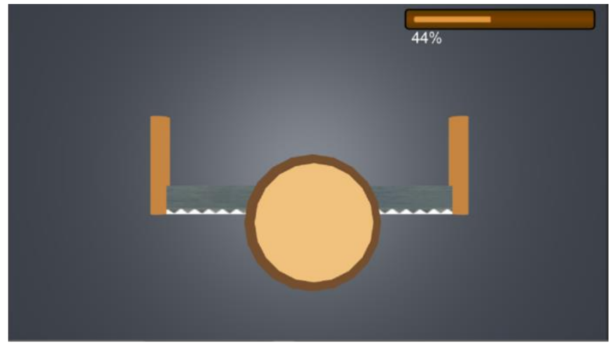

Figure 5b. Informational Display Screen During Joint Action Conditions. The team saw informed participants that they were not working on the task alone. The joint saw dropped vertically, only indicating task progress

position of each marker with sub-millimeter precision based off the established calibration of the cameras.

3.4.4 Experiment Guide

A custom SDK was written that translated streamed marker data in real time from Cortex to data usable by Unity. A custom Unity program was written to guide participants through the experiment. This Unity program took the information about each marker set (one for each participant, two total) and used those positions to drive a progress bar on the screen in front of the participants, showing them their progress throughout each trial. The program indicated to the participants when to start and stop each trial, while keeping track of all trial progress in the background. See Figure 5a for an example of what the display showed participants in the SA condition, and Figure 5b for an example of what participants saw during both PJA and FJA conditions.

3.5 Procedure

3.5.1 Pre-experimental preparations

Preparation work was required for the experiment space prior to each session. First, all breathing tubes and masks associated with the BIOPAC system were cleaned and sanitized using mild, soapy water and disinfecting wipes, then dried. The motion capture system was then calibrated by walking the space and waving the calibration wand to ensure all cameras were capturing accurately. After the room was ready, each table with the experimental apparatus was wheeled into place, ensuring perpendicularity with the global reference. The rolling cart containing all of the BIOPAC modules was then rolled into place next to the tables, and the amplifiers and sampling tubes were connected to the modules. The breathing tubes and masks were connected to the amplifier and mixing chamber, one for each participant. The BIOPAC system was turned on and allowed to warm up for 20 minutes. During this time, all cables were connected to their appropriate destinations. The ethernet cable was run from the PC to the BIOPAC box. An HDMI cable was run from the PC to the splitter box, which splits the signal to the two monitors on the tables. The analog signal cable that connects the BIOPAC box to the Cortex Signal box was plugged in to each. After the pumps in the amplifiers warmed up, the system was calibrated with a calibration gas to ensure accurate readings. The mixing chambers were then flushed with ambient room air, and the Unity program was started. The appropriate participant number was entered for each pair, and the session was ready to start.

3.5.2 Data Collection

Upon entering the experimental space participants were given an IRB approved consent form to read and sign. The form instructed them that they would be moving around, allowed breaks if they needed them, and could voluntarily withdraw at any point in the experiment.

While the participants read, the experimenter again stressed these important points and waited to receive verbal acknowledgement, in addition to written consent, that the participants understood the process. Demographics about each participant were collected, including age, gender, ethnicity, and handedness. The participants were instructed that they would be using the apparatus in front of them to “saw the logs” on the screen, and that there were three conditions consisting of 10 trials (trials were considered completed when participants moved the apparatus handle a total of 35 m; mean trial time was 34.14 s) with a 5 to 7 min break between the conditions. They were told that the trials in each condition would be performed back to back. Participants were asked to move at about 80% of their maximum possible speed but were allowed to determine this at their own discretion. This ensured participants exerted enough energy to register a change in RER, but not enough to prevent them from being able to maintain consistent performance throughout the experiment. Participants were then fit with the breathing masks and instructed to breathe regularly for two minutes to establish a baseline RER value. After the baseline was confirmed, participants were told that they would be sawing the log in front of them(see Figure 5a for what the screen would look like). They then performed 10 trials of the first condition, which was always SA, to establish their natural movement frequency. Instructions to start and stop sawing automatically appeared on the screen in front of the participants.

After the 10 trials, they were instructed to take a break and to continue to breathe regularly into the mask. The participants were then told that from here until the end of the experiment they would be working together in sawing the single log that appeared on the screen. Furthermore, they were told to maintain their individual 80% of max speed. In the PJA and FJA condition, participants sawed the entire log with two saw handles cutting into it (see Figure 5b).

Depending on the condition, the curtains separating the participants were either left closed (if PJA was the second condition) or open (if FJA was the second condition). When RER values returned to their established baseline, the next block started. The same process for the first block was followed for the second block. After trials 11-20 were completed, participants were again told to rest and the curtains were adjusted according to the next condition (open if FJA was next, closed if PJA was next). When RER values return to the resting rate, participants perform block three the same as block two. Afterwards, participants were debriefed and thanked for their time.

4 DATA ANALYSIS

4.1 Movement Data Processing and CRQA

Cross-Recurrence Quantification Analysis (CRQA) was performed to measure the degree of coordination and synchrony of participants' movements. CRQA involves the process of comparing the timeseries (see Figure 6 for an example timeseries from one trial for each condition) of one participants' movement data to their partner's movement data. CRQA (Marwan, Carmen Romano, Thiel, & Kurths, 2007; Shockley, 2005) compares the trajectories of the two time series in a reconstructed phase space and tallies the number of points of co-visitation in the reconstructed phase space.

Prior to running CRQA, the five required analysis parameters (delay, embedding dimension, radius, rescale, and normalization process) were chosen. A custom script was used to automatically determine the optimal parameters for each trial, and the parameters were chosen appropriately. A delay of 12 was chosen based on the results of an Average Mutual Information analysis run on each of the time series. The results of a False Nearest Neighbors Analysis determined the appropriate embedding dimension to be 5. A radius of 14 was chosen after

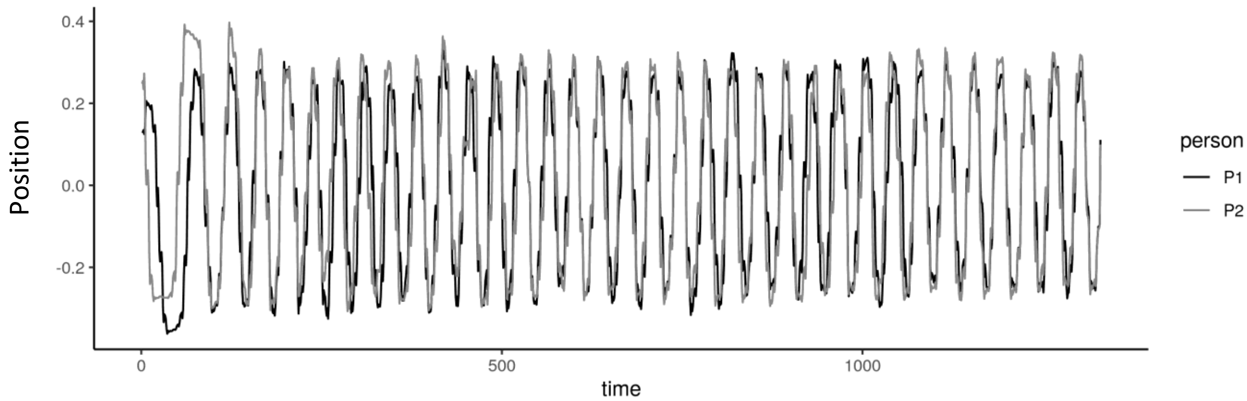

Figure 6a. Sample Timeseries from one FJA trial

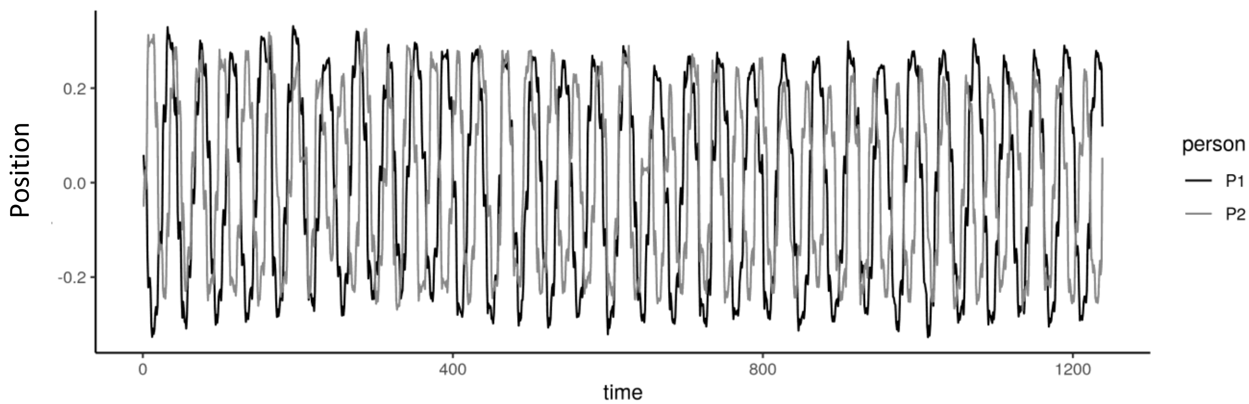

Figure 6b. Sample Timeseries from one PJA trial

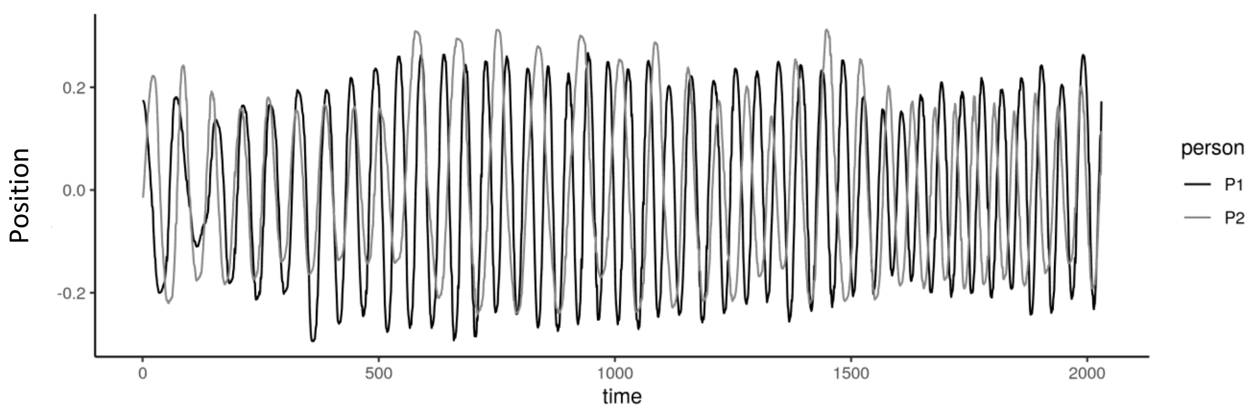

Figure 6c. Sample Timeseries from one SA trial

Figure 6. Sample timeseries of movement data for both participants in a FJA trial (Figure 6a), PJA trial (Figure 6b), and a SA trial (Figure 6c). Person 1's movement data is depicted in black and Person 2's movement data is depicted in lighter gray. Normalized position makes up the Y-axis, with Trial Time in seconds as the X-axis.

viewing a distribution of algorithmically decided optimum parameters. The data were rescaled using the max values and were normalized using the unit interval.

Levels of synchrony were measured using the CRQA variables Lmax (length of the longest diagonal line in the cross-recurrence plot) and %REC (percent recurrence; the percentage of points identified as points of co-visitation in reconstructed phase space).

4.2 Movement Data Processing

MATLAB (MathWorks) was used to interpolate loss of tracking in the movement data and create an individual timeseries of each participant's movement data for each trial. If the motion capture system lost tracking of the marker set for a limited number of frames, the frame before and frame after loss of tracking were identified, then the location of the missing marker set was determined through a linear fit between those two points. This interpolation created a flat, linear trajectory that lasted a maximum of 6 frames. All recorded data (energy expenditure and movement position) were also trimmed to exclude the first and last 10% (leaving the middle 80%) to eliminate transients.

4.3 RER Data Processing

To prepare the energy expenditure data captured from the BIOPAC, the RER data was normalized using a Min-Max normalization to account for a mismatch between the calibration of the expired gas analysis machines. The average RER per trial for each participant was then calculated. These averages from each trial were then averaged within conditions per participant giving one value per condition to submit for analysis.

4.4 Data Analysis

CRQA, as described above, compared the co-visitation of the partners' time series in reconstructed phase space as a way to measure movement coordination. Difference in Lmax and %REC between conditions were analyzed with a one-way ANOVA with jointness level as the

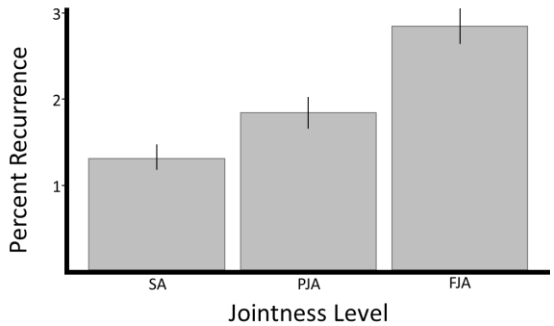

Figure 7a. Effect of Condition on Recurrence Rate of Participants' Movement

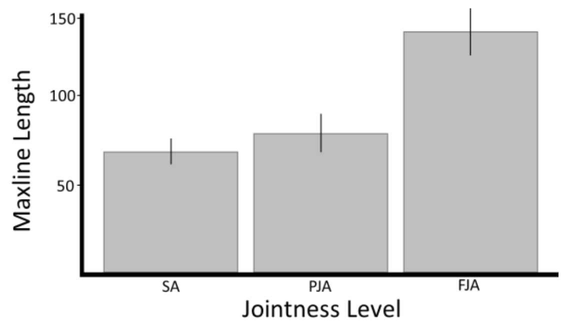

Figure 7b. Effect of Condition on Maxline Length of Participants' Movements

factor. A significantly higher %REC and Lmax value for FJA compared to SA and PJA would indicate that the experimental manipulation was successful, and participants synchronized their movements more during FJA trials. To test my hypothesis that synchronous coordination leads to different individual energy expenditure, this finding is a necessary first step because if %REC and Lmax values do not differ between the three conditions, this might indicate a failure to properly isolate participants in PJA and SA trials and would nullify any findings on energy expenditure.

To capture differences in energy expenditure between the three jointness levels (SA, PJA, and FJA), a repeated-measures ANOVA was performed on the participant RER averages per condition with Jointness Level and Participant as the factors.

5 RESULTS

5.1 Movement Data

To ensure that participants were properly isolated and did not exchange information or synchronize in the SA and PJA conditions but did exchange information and were able to synchronize their movements in the FJA condition, the movement data were submitted to CRQA. %REC and Lmax were subjected to a one-way ANOVA, comparing FJA to the

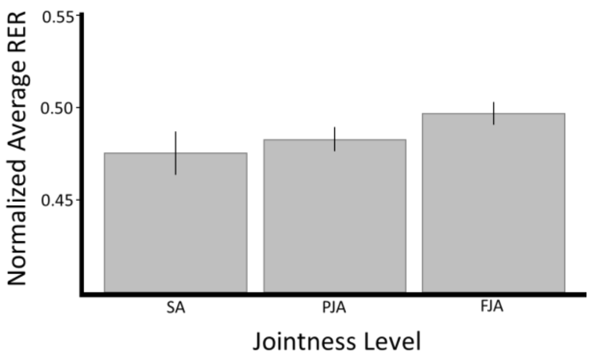

Figure 8a. Effect of Condition on Average RER of each participant

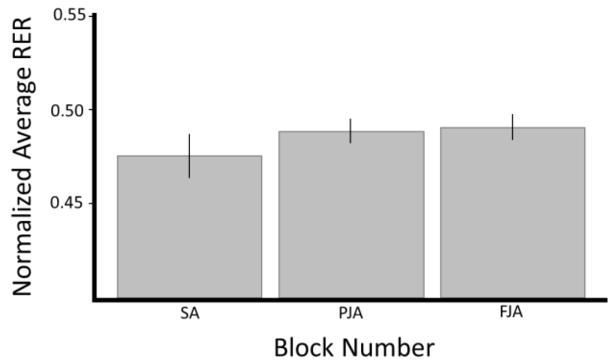

Figure 8b. Effect of Block Order on Average RER of each participant

remaining two conditions. The results showed a main effect of %REC, $F(2, 18) = 9.186$, $\eta p^2 = .47$, $p < .005$ (see Figure 7a). Tukey Post-Hoc analyses revealed that the mean %REC for participants was significantly greater during FJA than during SA, $t(18) = 3.89$, $p < .005$, and also during PJA, $t(18) = 2.56$, $p < .05$. Similarly, results revealed a marginally significant main effect of Lmax, $F(2, 18) = 3.29$, $\eta p^2 = .27$, $p = .06$ (see Figure 7b). Tukey Post-Hoc tests showed Lmax was marginally significantly longer in FJA than in SA, $t(18) = 2.43$, $p = .06$.

5.2 Energy Expenditure

5.2.1 By Condition

To assess the effect that Jointness Level had on the participants' energy expenditure, the RER data was subjected to a repeated-measures ANOVA. This analysis (see Figure 8a) revealed that there was no effect of Jointness Level, $F(2, 18) = 1.561$, $\eta p^2 = .16$ $p = .24$, nor of Participant, $F(1, 9) = 2.322$, $\eta p^2 = .22$, $p = .16$.

5.2.2 By Block

To test whether a learning effect seen in other motor theory work (Huang et al., 2012) is present in the current study, a repeated-measures ANOVA was conducted on the RER data divided into three blocks based on presentation order. This analysis (see Figure 8b) revealed no effect of Block order, $F(2, 18) = 0.69$, $\eta p^2 = .07$, $p = .51$, and nor of Participant, $F(1, 9) = 2.17$, $\eta p^2 = .19$, $p = .17$.

6 DISCUSSION

The current study examined the effects of different jointness levels on the energy expenditure of individuals. Single Action scenarios occur when one person is performing a task alone, with no outside influence from others. Pseudo Joint Action scenarios occur when two or more actors are working together on the same task but have no explicit mutual influence on each other's actions. Factual Joint Action scenarios occur when two or more actors engage in an action together that involves informational exchange (haptic, visual, auditory) allowing their movements to be coordinated.

When two people participate in joint action, the current consensus in the literature is that they use more energy to complete the task when they must deviate from their optimum movement frequency. When two people work together to lift an object, obviously they use less energy than when one person would try to lift the same object alone. When they are not physically connected, sharing the load of an object, though, what is the effect of coupling on energy expenditure? One line of thought indicates that energy expenditure increases when switching from working in SA to an FJA scenario, requiring the actors to leave their natural movement frequency in order to meet the other actor in the middle (Turvey et al., 1988; Wagnild & Wall-Scheffler, 2013). Any deviation from a person's most efficient movement frequency leads to an increase in energy expenditure. With this in mind, it would seem to be inefficient to work together on a task that does not involve two actors to join forces and move something together.

In the current study, consistent with previous findings in the literature, participants coordinated when they could see and hear each other while working in the level of FJA, but not when they were isolated working in the SA and PJA levels. Coordination emerges during rhythmic tasks when actors can exchange information about their movements (Richardson et al., 2007; Schmidt & O'Brien, 1997). This confirmation allowed me to analyze the energy expenditure data, knowing that the experimental manipulation of creating different levels of joint action was successful.

Contrary to my hypotheses, there were no differences in energy expenditure between any of the three conditions. This result was unexpected when viewed in light of previous literature (Ralston, 1958; Turvey et al., 1988; Wagnild & Wall-Scheffler, 2013). During FJA, participants that had different optimum movement frequencies had to deviate from their natural movement frequency in order to establish coordination which should lead to an increase in energy expenditure. In accordance with previous literature, the results would have shown no difference in participant energy expenditure between SA and PJA levels of joint action, but a significant increase in energy expenditure in the level of FJA. Future analyses will determine the extent that participants deviated from their optimum movement frequency by comparing their SA movement frequency to their FJA movement frequency. If the values significantly differ, an increase in expended energy would be expected.

However, my results did not show a significant difference between the amount of energy expended in the three conditions. There is, though, a trend showing actions during FJA used more energy than those of the other two conditions. This trend is consistent with the notion that when performing a non-mechanically coupled joint action task, people will exert more energy as a result of deviating from their optimum frequency than when they do not deviate from their optimum movement frequency when moving alone.

The results of the current study may be nonsignificant due to a small sample size, resulting in low power. Given a larger sample size, the trend these results demonstrate may become more pronounced and statistically significant. Another possible explanation for the current study's results may be in the experiment methodology itself (e.g., machine calibration, trial structure and execution, data collection and analysis methods). If either expired gas analysis machine is out of calibration, the RER values that it outputs could be either higher or lower than the real value which effects the ability to compare between participants. I did my best to account for this with the min-max normalization, but accurate machines from the start might yield different results. The data collection and analysis methods employed in this study could also impact the results, once again based on the normalization of the data.

Finally, it should be noted that the statistical analysis may not have adequately captured the rich resolution and detail of the RER and movement data. The timeseries gathered from both RER calculations and the movement data from each participant allows for continuous assessment of energy expenditure and movement profiles not captured by the simple averages that were taken for this study's analyses. By increasing the detail of analysis and investigating how these values change continuously within each trial, instead of just looking at how one descriptor changes between them, these results may change to be more in line with previous research. Further data collection and exploration can address these issues and investigate the details within the experiment.

6.1 Limitations and Future Directions

A limitation of this study was that the sample size was quite small. As a result, the current study may have limited statistical power.

Another limitation was that additional analyses of the data were possible. The data gathered from the expired gas analysis is high-resolution, continuous data that appear to change quite a lot during each trial. A sliding window cross-correlation on the energy expenditure data might reveal the difference originally hypothesized of how the coupling strength between participants affects their immediate energy expenditure.

It may also have been helpful to focus the analyses only at the later trials in each block. A "ramping up" trend appeared in the first three or four trials of each block as the participants get back into the activity after returning to their resting rate. By looking at only the later trials, a more representative energy expenditure value may show a difference between conditions and blocks that is more in line with previous research.

An experiment similar to this one is being developed to implement with a human-robot pair. Since the robot's movements can be programmed, this allows the testing of how different levels of adaptation to a partner's movements correlates with energy expenditure. Scaling the level of adaptation a robot has to its human partner creates different situations that force the human partner to adapt their movements in order to stay synchronized.

Another planned experiment building upon this paradigm will haptically connect the two partners. By providing a physical linkage between the two, more drastic changes in energy expenditure between the different conditions, and different connections, are expected to emerge (Cuijpers, Den Hartigh, Zaal, & de Poel, 2019).

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