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"Cues to Joint Agency - A Theoretical and Empirical Investigation of the Sense of Agency in Joint Action"

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Abstract

Perceiving oneself as the author of one's actions and their effects in the environment - the *sense of agency* (SoA) - is a central feature of human experience and self-awareness. As previous research on SoA has mainly addressed actions carried out by single individuals, an open question is, how SoA is constituted during *joint action*. Recent proposals suggest that people's agentive experience in joint action reflects a sense of *joint agency*, meaning that the experienced unit of agency extends beyond the individual to the group as a whole. Although recent studies provide evidence for this proposal, still very little is known about the sources and mechanisms underlying the sense of joint agency. Targeting this gap, it was explored what cues people use to sense agency in different joint action contexts.

An experiment was conducted to investigate the influence of sensorimotor, perceptual, and cognitive cues to agency in a joint sequence reproduction task. Pairs of participants coordinated finger taps under different coordination demands (high: alternating tapping; low: sequential tapping) to reproduce the tempo of a short metronome tone sequence and reported whether tones heard during tapping had either been controlled by them (joint control) or by a computer instead (external control). Additionally, participants rated their agentive experience after each sequence on a scale that ranged from shared to individual control.

Overall, participants reported stronger feelings of shared as opposed to individual control, indicating that people do experience joint agency during joint action. Against findings from previous studies, coordination demands were not found to moderate this effect. Coordination demands had also no effect on participants' ability to distinguish between joint and external control mode. Response-locked analysis of participants tapping performance revealed that independent of coordination demands, both sensorimotor and perceptual cues were used to sense agency. Additionally, there was evidence for an influence of cognitive cues and motivational factors on participants' responses, again irrespective of coordination demands.

The results suggest that the sense of joint agency stems from an integration of both private sensorimotor cues and publicly accessible perceptual cues and may be furthermore influenced by cognitive and motivational factors. This points out that the sense of joint agency is highly likely generated through a mechanism that weights and integrates multiple cues tight to the monitoring of self-, other- and jointly produced action effects at different levels of action specification and control. However, the current study was unable to yield evidence for a specific weighting of certain agency cues as a function of the strength of the sense of joint agency. Implications for theories of joint agency and future research are discussed.

Zusammenfassung

Wir erleben in der Regel ein unmittelbares Gefühl der Urheberschaft und Kontrolle über unsere alltäglichen Handlungen und den daraus resultierenden Effekten in unserer Umwelt. Die Präsenz dieses Handlungskontrollerleben (englisch: sense of agency) ist ein zentrales Merkmal menschlicher Erfahrung und inhärenter Bestandteil unseres bewussten Selbsterlebens. Bisherige kognitionswissenschaftliche Forschung zur Entstehung dieses Phänomens blieb dabei bis vor kurzem auf Handlungen beschränkt, die von einzelnen Individuen ausgeführt werden. Wie sich das Handlungskontrollerleben hingegen in Situationen konstituiert in denen mehre Individuen gemeinsam handeln, wirft derzeit noch viele offene Fragen auf. Jüngste philosophische Abhandlungen und empirische Forschungsarbeiten zu diesem Thema legen nahe, dass das Handlungskontrollerleben in gemeinsamen Handlungskontexten nicht auf individuelle Handlungen beschränkt bleibt, sondern vielmehr ein gemeinsames Handlungskontrollerleben auf der Gruppenebene wiederspiegelt. Allerdings ist bisher wenig darüber bekannt, welche Mechanismen diesem besonderen, gemeinsamen Handeln beiwohnenden, Erleben zugrunde liegen und auf Basis welcher Information sich dieses zusammensetzt. Die Vorliegende Arbeit stellt einen Versuch da, diese Forschungslücke zu füllen, in dem sie den Einfluss sensumotorischer, wahrnehmungsbezogener und kognitiver informativer Signale auf die Genese des Handlungskontrollerleben in unterschiedlichen gemeinsamen Handlungskontexten untersucht.

Dazu wurde das Handlungskontrollerleben von Personen in einer gemeinsamen Sequenzreproduktionsaufgabe experimentell untersucht. Paare von Versuchsteilnehmenden bekamen die Aufgabe, Tastendrücke unter verschiedenen Koordinationsanforderungen (hoch: abwechselndes drücken; niedrig: sequentielles drücken) so auf einander abzustimmen, dass sie das Tempo einer kurzen gleichförmigen Tonsequenz möglichst akkurat reproduzierten und gaben nach jedem Durchgang an, ob die Töne die sie während des Drückens gehört hatten von ihnen (gemeinsame Kontrolle) oder von einem Computer (externe Kontrolle) kontrolliert worden waren. Außerdem bewerteten die Teilnehmenden ihr Handlungskontrollerleben über die gehörten Töne nach jedem Durchgang auf einer Skala mit den Endpunkten geteilte und individuelle Kontrolle.

Insgesamt gaben die Teilnehmenden ein stärker ausgeprägtes Erleben geteilter im Gegensatz zu individueller Kontrolle über die gehörten Töne an, was darauf hinweist, dass Personen ein Gefühl geteilter Handlungskontrolle erleben, wenn sie eng mit anderen Personen zusammenhandeln. Entgegen Ergebnissen früherer Studien zeigte sich allerdings, dass das

Erleben gemeinsamer Handlungskontrolle nicht durch die Höhe der Koordinationsanforderungen an die Teilnehmenden beeinflusst war. Die Höhe der Koordinationsanforderungen hatte auch keinen Einfluss auf die Fähigkeit, zwischen den beiden Kontrollmodi zu diskriminieren. Die Analyse der Timingperformanz ergab, dass die Teilnehmenden, unabhängig von den jeweiligen Koordinationsanforderungen, sowohl auf sensumotorische als auch auf wahrnehmungsbezogene Information zurückgriffen, um das Ausmaß der gemeinsamen Handlungskontrolle zu evaluieren. Es zeigten sich außerdem Hinweise darauf, dass das gemeinsame Handlungskontrollerleben zudem von kognitiven und motivationalen Faktoren beeinflusst werden kann.

Die Ergebnisse legen nahe, dass das Erleben gemeinsamer Handlungskontrolle sowohl auf Information beruht die direkt mit dem Ausführen eigener motorischer Handlungen verknüpft ist, als auch auf wahrnehmungsbezogener Information die allen Teilnehmenden der gemeinsamen Handlungssituation zu gleichen Maßen zur Verfügung steht und zudem von kognitiven Faktoren beeinflusst werden kann. Die Ergebnisse weisen damit darauf hin, dass dem Erleben gemeinsamer Handlungskontrolle sehr wahrscheinlich ein Mechanismus zugrunde liegt, der Informationen aus mehreren Quellen gewichtet integriert, um ein akkurates und kohärentes Gefühl der Handlungskontrolle in gemeinsamen Handlungskontexten zu generieren. Hinweise auf eine Unterschiedliche Gewichtung bestimmter informativer Quellen in Abhängigkeit von der Ausprägung des Erlebens gemeinsamer Handlungskontrolle konnten in dieser Studie allerdings nicht gezeigt werden. Sich daraus ergebende Implikationen für Theorien zur Entstehung des Erlebens gemeinsamer Handlungskontrolle und für zukünftige Forschung werden diskutiert.

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1. Introduction

1.1. Scope and relevance

It is in great part through our actions and their consequences that we become aware of us as individual entities in the world. Without the ability to induce changes in the environment by acting upon it - to make things happen in the world - our existence would be questionable, our self-recognition as *agents* would be groundless. Agency, thus, marks a fundamental condition of human existence, and understanding the cognitive foundations of action-related phenomena is a central challenge for cognitive science. One outstanding phenomenon in the domain of action is the profound and pervasive experience that we usually feel to be in control of what we are doing and of how the world around us changes accordingly. We usually feel in charge of our actions and, through them, of the unfolding events around us. This central feature of human experience and self-awareness has been termed the *sense of agency* (SoA) (Haggard & Tsakiris, 2009). Understanding the origins of this experience has occupied cognitive scientists and philosophers alike for many decades now as SoA is not only of key relevance for our understanding of the self and the human mind more broadly but also of major importance for our civilization and society, given its impact on health and well-being and its connection to the concept of responsibility (Haggard, 2017; Moore, 2016).

Moreover, we rarely act in isolation but most often together with others to make things happen in the world. We shake hands and clink glasses, we lift heavy objects and prepare meals together, we make music with others and create goods in collaboration. Such instances of social interactions in which multiple individuals coordinate their actions to elicit changes in their environment - *joint action* (Sebanz et al., 2006) – mark regular instances of our daily activities and determine a core aspect of human sociality. Crucially, joint actions also add complexity to the sense of agency as answering how people experience agency in these situations is not at all straightforward.

For illustration, consider the example of two people paddling a canoe down a river. Both people can affect the curse of the canoe by strokes of their paddles and both aim to keep the canoes trajectory in the fast-floating water in the middle of the river, to avoid crashing into obstacles and to hold the canoe stable to avoid capsize. As the two people paddle along the river, how do they experience agency over their actions and the trajectory of the canoe? Do they feel less agency as they would when paddling alone in a single canoe or can the presence of their co-actor even enhance their sense of agency? Is it important, that the person in the back has a stronger impact on the trajectory of the canoe, or do both people feel the same amount of agency? Does the individual performance of each person determine how much agency they feel or is their sense of agency mainly dependent on the overall success of keeping the canoe fast and stable? Does their sense of agency differ only quantitively compared to the case when paddling alone or is their agentive experience in the joint action scenario of a whole new quality? That is to say that the experienced unit of agency may extend beyond each individual to the dyad as a whole. If that is the case, what information do both people take into account to evaluate how much they are in control of the canoe and what are the mechanisms that give rise to this special agentive experience in joint action contexts?

It should become clear that the investigation of SoA in joint action contexts confronts us with numerous problems. We are confronted with problems about the strength of peoples SoA in joint action contexts, about their agentive identity, and about the cues and mechanisms that give rise to their specific agentive experience. Answers to them are not only important for a better theoretical understanding of SoA but raise also practical implications for e.g. the design of joint tasks, the distribution of blame and gratitude, or the adjudgment of responsibility for joint action outcomes. Considering these points, the centrality of SoA for human experience and the vast number of instances where people act together with others, it is striking that research on the intersection of SoA and joint action has remained sparse until recently.

This thesis aims to provide an overview of the current state of research on the topic of SoA in joint action and to expand our knowledge about it by empirically investigating what cues people use to sense agency in different joint action contexts. Thereby the thesis focusses on the proposal that peoples agentive experience during joint action constitutes a special case of SoA conceptualized as a sense of *joint agency*, which reflects the idea that the experienced unit of agency in joint action context is centred at the group and not only at the single individuals engaged in the joint action (Dokic, 2010; Pacherie, 2012, 2014; Seemann, 2009).

In the remainder of this chapter, I will first give a recap of previous research on SoA, joint action, and their intersection. This includes a summary of the cues and mechanisms that are currently discussed to explain the generation of SoA for individual actions and an overview of the coordination processes and representations supporting successful joint action. This is followed by a discussion of arising challenges for accounts of SoA in joint action along with a review of previous empirical findings addressing them. This will lead to the formulation of the research question and hypotheses standing behind the empirical part of this thesis.

1.2. Previous research

Research on SoA has flourished in cognitive science over the last two decades. Advances in this field have been mainly brought forward by the development of experimental methods and paradigms suitable to trace the cognitive and neural underpinnings of this pervasive experience and its alterations in cases of psychopathology (see Haggard, 2017 for a recent review). Nearly at the same time, there has also been a great increase of interest among cognitive scientists in the topic of joint action which has led to the establishment of a considerable body of knowledge about how people plan and coordinate their actions together with others (see Vesper & Sebanz, 2016 for a recent review). However, systematic attempts to establish connections between these two active research domains have been brought forward only very recently (e.g. Pacherie, 2014). Before turning to them, we shall first have a look at previous research on SoA for individual actions and on the topic of joint action respectively.

1.2.1. Self-agency: Cues, mechanisms, and models

The general scope of research on SoA is to explain, how and where the sense of agency for individual actions is generated within the cognitive system. Thus, a central focus of research on SoA has been to investigate what cues affect the experience of self-agency and what mechanisms give rise to their formation and impact. Over the years, this has led to the identification of several cues to self-agency and to the proposal of different cognitive models explaining the formation of SoA for individual actions.

Sensorimotor cues to agency

Several accounts of SoA highlight a central importance of internal sensorimotor cues for the generation of feelings of self-agency. Sensorimotor cues to agency can be understood as informative signals about the source of an observed event (self-caused vs. externally caused) that become available through the generation and execution of motor acts. Accordingly, sensorimotor accounts of SoA link the generation of SoA to low-level mechanisms within the motor system that are involved in the planning and online monitoring of self-executed actions.

Sensorimotor accounts of SoA originate in computational theories of motor control and extend their explanatory scope to the experience of self-agency. According to these theories, when the motor system generates a motor command, an *efference copy* of this command is passed to an internal *forward model* that computes a prediction of the sensory consequences expected to result from the execution of that motor command (Wolpert & Miall, 1996). The predicted sensory consequences are then compared to the actual sensory feedback obtained through action execution (re-afferences) which allows for fast and effective online monitoring and control of goal-directed movement. According to the influential *comparator model*, the very same processes are also responsible for the generation of SoA. When the predicted sensory consequences of an issued motor command match subsequent afferent sensory feedback, people perceive the sensory events as self-caused, discrepancies on the other hand undermine the generation of SoA (Frith et al., 2000). Under this account, it is the discrepancy between movement-based predicted and actually observed sensory events that provide sensorimotor cues to agency.

Evidence for this account is provided by studies showing that SoA decreases when discrepancies between internally predicted and actual observed consequences of one's movements are high due to spatial deviations or temporal delays (Knoblich & Kircher, 2004; Sato & Yasuda, 2005).

Perceptual cues to agency

Other researchers have pointed to a crucial role of performance-related perceptual cues for SoA (Jeannerod, 2009; Knoblich & Repp, 2009; Pacherie, 2008, 2010; van der Wel & Knoblich, 2013). Whereas sensorimotor accounts focus on processes underlying the online monitoring of movement execution, these accounts focus on processes that monitor the perceptual events resulting from action execution irrespective of the specific motor commands that gave rise to them. Thus, perceptual cues to agency can be understood as informative signals about the source of an observed event that become available through the purely perceptual unfolding of these events over time. This ties perceptual cues to an intermediate level of action specification in which actions are represented by the perceptual events they bring about in the environment and not in terms of specific motor commands (Hommel et al., 2001; Pacherie, 2008; Prinz, 1997).

Predictive processes in the motor system and their involvement in the monitoring of action execution still receive a central role for the generation of SoA in these accounts. However, it is pointed out that the motor system can generate predictions about the sensory consequences of an action at different levels of grain and that predictions of the sensory consequences based on internal motor commands can be dissociated from predictions of sensory consequences on a more peripheral level (Jeannerod, 2009; Pacherie, 2010). Whereas the former can provide reliable cues for the fact *that* one is acting, the letter is assumed to be of more central importance for SoA, because they inform the cognitive system additionally about *what* actually happens over the course of one's actions. Thus, perceptual accounts of SoA suggest that the comparison between the predicted and actual *perceptual* effects of one's actions marks the central source for SoA whereas sensory predictions based on one's motor commands serve merely the online control of self-generated actions.

Evidence for these claims comes from studies showing that people's awareness of their own motor performance is principally low and that substantial adjustments of movements can remain unnoticed as long as the resulting perceptual effects unfold as intended (Fourneret & Jeannerod, 1998). Furthermore, schizophrenic patients who show severe impairments of SoA retain an intact capacity for automatic sensorimotor control (Fourneret et al., 2002). Although there is even direct evidence for a substantial role of perceptual cues in the generation of SoA (Knoblich & Repp, 2009), it should be noted that perceptual information alone is inherently ambiguous with regard to the causal origin of an observed event (cf. Jeannerod, 1999). This generates problems for the reliability of SoA when it is generated on perceptual cues alone and stresses a necessity for accounts to integrate contributions of perceptual cues with other mechanisms (Jeannerod, 1999; van der Wel & Knoblich, 2013). On the same side it can also explain the regular instances of an illusory SoA when one experiences an external perceptual event (such as the lighting up of a lamp) as caused by a coincidental action of oneself (such as a click on one's computer mouse).

Cognitive cues to agency

The fact that SoA can arise in absence of any causal relationship between one's actions and observed sensory events has even led some researchers to deny an important contribution of the motor system in the generation of SoA completely. Instead, these researchers propose that SoA is generated through reflective higher-order inferential (Wegner & Wheatley, 1999) and holistic interpretative processes (Stephens & Graham, 2000) that operate independently from the processes underlying action execution and monitoring. In these accounts, cognitive cues provide the primary source for SoA that can be understood as informative signals about the source of an event that become available through a post-hoc matching of the observed event with higher-order mental states such as beliefs, expectations and distal intentions or narrative conceptions of the self.

One of the most influential accounts that argues along these lines is Wegner's *theory of apparent mental causation* (Wegner, 2002; Wegner & Wheatley, 1999). This account states that SoA is the product of a fallible inferential process in which an observed event is retrospectively attributed to the self. This inference takes place, and hence SoA arises, when the observed event is found to be congruent with a previously hold intention to act. This is said to be the case if the intention preceded the event, is consistent with the event and if no other obvious alternative causes for the event are available. Implications of this account are that SoA can arise even in the absence of any self-executed action (as holding an intention to act is sufficient for the inference) and that SoA is highly dependent on external, situational cues that may impact the inferential process.

Evidence for this account and for the impact of cognitive cues on SoA comes from studies showing that priming of action effects prior to the observation of an event enhances SoA (Aarts et al., 2005; Moore et al., 2009) and that priming a distal intention can even elicit a vicarious SoA for events that were in fact not produced by the agent (Wegner et al., 2004; Wegner & Wheatley, 1999). Furthermore, it has been shown that SoA can be subject to other contextual parameters such as manipulations of causal beliefs (Desantis et al., 2011).

Integrative frameworks for the sense of agency

There is now a converging consensus that none of the outlined agency cues nor any of the outlined models alone can account for the full complexity of SoA. Instead, more recent accounts of SoA are committed to the view that SoA is subject to a multiplicity of cues stemming both from predictive processes underlying the execution and monitoring of actions as well as from retrospective higher-order inferential and interpretative processes (Bayne & Pacherie, 2007; Knoblich & Repp, 2009; Moore et al., 2009; Moore & Fletcher, 2012; Synofzik et al., 2013).

A promising approach to account for the complex interplay of different agency cues and mechanisms underlying the generation of SoA is to appeal to a hierarchical framework of action specification and control (Pacherie, 2008) together with accounts of optimal cue integration (Moore & Fletcher, 2012; Synofzik et al., 2009). In Pacherie's (2008) conceptual framework for the phenomenology of action, SoA relies on the congruence between the anticipated and actual outcome of an action that is evaluated at different hierarchical levels of action specification and control. At the highest level, action outcomes are specified in cognitive terms reflecting ultimate or future-oriented goals of an action (distal intentions), at an intermediate level in terms of the perceptual events occurring as a consequence of executing a situationally anchored action plan (proximal intentions) and at the lowest level in sensorimotor terms specifying the precise motor commands and immediate sensory effects of a motor act (motor intentions). Congruency between anticipated and actual action outcomes is evaluated at all levels in this hierarchy which yields a multiplicity of different cues to agency (cognitive, perceptual, and sensorimotor) that mutually contribute to the generation of SoA. An explanation of how this interplay between different agency cues may be realized by the cognitive system is provided by accounts of optimal cue integration (Moore & Fletcher, 2012; Synofzik et al., 2009, 2013). According to these accounts, to come up with an accurate, robust, and flexible conception of its current agentive state, the cognitive system constantly exploits all agency cues available and integrates them based on their relative reliability in a given situation. Thus, it is assumed that different agency cues get weighted based on the reliability of their informative content which determines their relative contribution to the generation of SoA and which can vary from context to context. If, for example, the prior expectation that one's actions are causing a particular event in the environment is very strong due to priming of action intentions or contextual information, cognitive cues resulting from the congruency between that expectation and the observed event would receive a high weight and may rule out available contributions of the motor system that recorded discrepancies between internal predictions and sensory feedback. Conversely, if discrepancies between internal predictions and sensory feedback recorded by the motor system are very salient due to large temporal delays or spatial discrepancies between motor acts and subsequent sensory events, weights on sensorimotor or perceptual cues would be strengthened which would result in a stronger relative influence of these cues on the experience of agency.

Summary

As outlined in the previous subchapters, SoA for individual action seems to rely on cognitive, perceptual, and sensorimotor cues that are linked to different hierarchical levels of action specification and control. Recent integrative accounts provide an elegant way of combining previous cognitive models of SoA in a common framework that can account for the various findings on the contribution of these different cues to agency. If taken for granted, future research on SoA could turn towards the investigation of the factors that can alter the relative weighting of agency cues. As shall become clear throughout the rest of this chapter, joint action contexts hold the potential to turn out as such factors. To explain how this assumption is justified, the next section provides an overview of models and research findings focussing on the representations and coordination processes supporting successful joint action.

1.2.2. Joint action: Coordination mechanisms and representations

So far, the discussion of SoA was limited to instances in which people act in isolation. As research on SoA started out to explain the sources and conditions that underly the pervasive phenomenon of experiencing *oneself* as the author of observed events in the environment (i.e. the sense of self-agency), this scope is reasonable. However, the recently growing interest in the topic of joint action calls for a shift in this perspective by investigating how SoA is constituted in cases in which multiple individuals coordinate their actions in space and time to bring about changes in their environment. As a premise for this endeavour, it is assumed that, as is with the case of individual actions, SoA in joint action originates from a multiplicity of cues that are linked to different processes of action specification and control. However, as the action specification and control processes underlying joint action are necessarily more complex than those underlying purely individual actions, we must first look at the specific cognitive, perceptual and motor mechanisms that underly the successful performance and control of joint action, before turning to the question how SoA may be constituted in these contexts.

For a joint action to turn out successfully, people engaged in a joint activity must coordinate their actions in space and time both with respect to each other as well as with respect to the joint goal they are trying to achieve. In recent years, research on joint action has identified several mechanisms that enable and support such online coordination processes. As shall become clear, these mechanisms bear direct implications for the constitution of SoA in joint action contexts.

Perception-action coupling

Many cognitive theories of action point out an inherent link between action and perception. According to the common coding theory and related accounts (Hommel et al., 2001; Jeannerod, 1999; Prinz, 1997), actions are encoded in a functionally equivalent way to perceptual representations, namely by the distal perceptual events they produce in the environment. Building up on the ideo-motor principle (James, 1890), common coding of action and perception implies that perceiving an action will automatically activate the corresponding action representation in the observer. This motor resonance mechanism would allow people to directly match an observed action onto their own motor repertoire and supports online coordination in joint action because it aligns co-actors observing each other by evoking congruent action tendencies among them (Knoblich et al., 2011). Moreover, this motor resonance mechanism is discussed as a means for getting access to another agents current action goal, which would allow a basic understanding of what another person is currently doing (Rizzolatti & Sinigaglia, 2010). Common coding of action and perceptual representations and the implied resonance mechanism is supported by behavioural and neuroscientific evidence. Behavioural studies have shown that perceiving an action evokes a tendency to carry it out even if not intended and critically affects the subsequent performance of concurrent actions (Heyes, 2011). On the other side is has been shown that action observation is highly affected by the current state of an observer’s motor system (Schütz-Bosbach & Prinz, 2007). On a neural level, common coding is supported by the finding of mirror neurons in brain areas of macaque monkeys and equivalent mirror systems in the human brain that are active both during action execution and during perception of similar actions by others (Rizzolatti & Craighero, 2004).

Action simulation and prediction

Successful online coordination between people does not only require them to understand what others are currently doing. To keep track of the unfolding actions and to adjust their own actions accordingly, people must also anticipate what consequences the actions of others bring about.

During action observation, the outlined coupling of perception and action is also assumed to provide the basis for real-time predictions of the outcomes of other's actions (Wilson & Knoblich, 2005). It is assumed that matching an observed action onto one's own motor repertoire allows people to exploit internal predictive models in their own motor system to issue predictions of the expected consequences of an observed action (Wolpert et al., 2003; Wolpert & Miall, 1996). Thus, internal models that usually guide an agent's own action execution could get exploited to simulate observed actions in real-time for predicting their outcomes. Such online simulation of observed actions is assumed to support successful coordination in joint action because it aligns expectations about the unfolding consequences of actions among multiple agents and induces congruent action tendencies for future actions (Knoblich et al., 2011). Evidence that this mechanism is in play during action observation is provided by studies showing that high compared to low similarity between an observed action and an observer's own motor repertoire due to motor expertise or the observation of an observer's own previous actions yields better predictions of action outcomes (Aglioti et al., 2008; Knoblich & Flach, 2001).

Moreover, action simulation must not be exclusively linked to the actual observation of another's action (Sebanz & Knoblich, 2009). Instead, it is assumed that people can exploit internal models of their own motor system offline (i.e. not tight to direct observation or execution of an action) to generate predictions of the outcomes of other's actions. This mechanism can support successful coordination in joint action because it would allow people to plan their own actions with respect to predictions of the unobserved or future unfolding of other's actions. Basic evidence for a mechanism of offline action simulation is provided by the finding that imagining an action activates the very same neural structures that underly the perception and execution of an action, extending the common representational format of action and perception to motor imagery (Decety & Grèzes, 2006). Furthermore, studies have shown that as soon people know what another person's task is, motor activation is found not only when people observe another person's action, but also if action observation is replaced by a symbolic cue announcing the action of the other (Kilner et al., 2004; Ramnani & Miall, 2004). It must be noted however that offline action simulation in joint action presupposes that people have an initial understanding of another person's contribution to the joint task that is decoupled from direct action observation. This, in turn, makes it necessary for people to possess representations of the joint task that include their own as well as other's contributions to the joint activity. How such representations are formed and constituted in joint action is outlined next.

Shared representations for goals and tasks

It was noted that planning one's own actions in relation to the unfolding of other's actions and in relation to joint action outcomes makes it necessary that people form representations of specific aspects of the joint activity. According to minimal accounts of joint action, the basic requirement for an intentional joint action involving planned coordination between multiple agents is that the engaged agents possess representations specifying the intended outcome of the joint activity (i.e. a joint action goal), their own part in achieving the joint goal and some knowledge that the joint goal will only be achieved through additional contributions of other agents (Vesper et al., 2010). Thus, under minimal requirements, people engaged in joint action must plan and adjust their own actions with respect to the intended joint outcome of the activity. Most often, though, people have access to more detailed information about a joint activity including knowledge about another persons' task. Co-representing such information would provide people with knowledge about the conditions under which others will perform certain actions. Co-representing other's tasks would then enable simulation of other's actions and prediction of their consequences even without directly observing them (Sebanz & Knoblich, 2009). Moreover, shared task representations are assumed to provide effective control structures for action monitoring and control during joint action (Knoblich et al., 2011). Knowing what another person's task is, allows people to compare simulations of what another person should do with the actual unfolding of their actions and thus enables error detection of actions executed by other people. This, in turn, allows people to rapidly adjust their own actions or to compensate for the errors of others, backing up successful coordination towards the desired outcome of the joint activity. A great body of evidence indicates that people readily form representations that specify not only their own but also the task performed by their co-actors, even if not necessary or detrimental for their own performance (Atmaca et al., 2008;

Sebanz et al., 2003, 2005) and that task co-representation effects action monitoring (Schuch & Tipper, 2007) and prediction (Ramnani & Miall, 2004) in joint action. In sum, this indicates that in most instances of intentional joint action, people's performance is guided by mental representations that specify 1) the intended outcome of the joint activity (joint action goal), 2) their own part in achieving that outcome together with others and 3) the respective part of one's co-actors (Knoblich & Sebanz, 2008).

An integrative model for join action

This special representational structure underlying joint action implies that action production in joint action relies on a complex interplay between monitoring and control processes of one's own actions, of the actions executed by other agents and of the joint effects resulting from their interplay all with respect to the overarching joint action goal. How could an integration of these processes be achieved by the cognitive system? One recent proposal by Keller, Novembre, and Loehr (2016) suggests that the production and control of coordinated joint action is achieved through the parallel working of three types of internal predictive models within the individual agents. The task of these models is to issue predictions about the unfolding consequences of the joint action including self-, other- and jointly produced action effects and to trigger action adjustments in the interacting agents if divergence from own, others' or joint action goals is detected. Internal models for self-produced actions ('self' internal models) refer to the forward models of action control that were already outlined in the previous chapter and fulfil the task of issuing predictions about the sensory consequences resulting from one's own actions. These predictions are evaluated against the agent's representation of his/her own part in the joint activity and trigger self-adjustments if necessary. At the same time, internal models for other-produced actions ('other' internal models) run in parallel to predict the actions and resulting consequences of co-actors. This is assumed to be achieved through the action simulation process described above that can either rely on bottom-up perception-action coupling during direct action observation or on the top-down influence of shared task representations. These predictions are evaluated against the agent's representation of the co-actor's part in the joint activity and allow the agent to adjust his/her actions to what others are doing and to compensate for potential errors of co-actors. The outputs of the internal models for self- and other-produced actions get further integrated by internal models for jointly produced actions ('joint' internal models) that yield predictions of the combined sensory consequences of self- and other-generated actions. This joint prediction is then evaluated against the agent's representation of the joint action goal which allows monitoring progress towards the desired outcome of the joint activity. Detection of divergence can then trigger action adjustments in the different agents with respect to the joint goal.

Summary

To summarize the previous subchapters, coordinated joint action relies on the interplay between internal predictive models for self-, other- and jointly produced action effects that evaluate the unfolding actions arising in a joint activity with respect to representations of a joint action goal, an agent's own part in the joint action and the parts of the involved co-actors. Common coding of perception and action provides the representational platform that allows integration of own and others' actions. Prediction of other- and jointly produced action effects is made possible through action simulation processes that build on perception-action coupling during direct action observation or on shared task representations that enable offline action simulation. These specificities of action specification and control in joint action bear direct implications for the SoA people experience in joint action contexts, as will be elaborated in the remainder of this chapter.

1.2.3. SoA for joint action: Challenges and empirical findings

After discussing the origins of SoA for individual actions and the coordination processes and representations underlying successful joint action, we shall now turn to the issue of how SoA might be constituted in joint action contexts. In the discussion of SoA for individual action, we reached the conclusion that SoA relies on sensorimotor, perceptual, and cognitive cues that are linked to specific levels of action specification and control. Under the assumption that the same holds for the SoA people experience during joint action, we must consider what implications the specificities of action specification and control that underly successful joint action bear for the constitution of SoA in joint action contexts and what challenges arise out of them. After discussing these implications and challenges, some recent empirical studies addressing them will be outlined.

Action specification and control in joint action: Implications for SoA

First, common coding of perception and action bears direct implications for SoA in joint action contexts. As the representations activated through action execution and action observation are functionally equivalent, they are not by themselves sufficient to inform the cognitive system whether an event was produced by oneself or by another agent (Jeannerod, 1999). Thus, common codes for action and perception are inherently ambiguous with regard to agency, which implies uncertainty about who caused an event in the environment on this level of action specification. On the one hand, this can account for vicarious experiences of self-agency and confusions of agency attributions between self and others and on the other hand stresses the importance of mechanisms enabling self-other discrimination to account for a veridical SoA in the domain of joint action. Potentially, however, as pointed out by Pacherie (2012, 2014), it might be exactly the degradation of self-other discrimination that could explain particular experiences of we-ness or synergy that can arise during joint action. The greater the challenge for self-other discrimination, the more likely it could get that people's agentive identity dissolves into the collective agency of the group, a phenomenon Pacherie (2012, 2014) labels as *we-agency*.

Beyond common coding and the problem of self-other discrimination, a second implication for the re-examination of SoA in joint action contexts is raised by the process of action simulation through the exploitation of internal predictive models in the motor system. As outlined above, predictive processes in the motor system receive a central role in explaining the generation of SoA for self-executed actions. The proposal that functionally similar processes are also at place to predict the unfolding consequences of others' actions, opens up the possibility that action simulation could also be used to monitor agency in others. Thus, besides enabling anticipatory action planning and adaptation with respect to others' actions and their potential errors, action simulation could also allow people to track the current amount of agency likely experienced by others. Given this potential for a parallel monitoring of one's own as well as other's agency, the question arises to what extent people engaged in a joint action take their co-actors agency into account to derive an overall SoA for the joint activity. Namely, instead of being solely related to individual action execution, SoA in joint action could be evaluated at the level of the group encompassing the performance of co-actors (Dewey & Knoblich, 2014). Accordingly, SoA in joint action could be additionally affected by predictions of other-produced action effects that may yield agency cues linked to the performance of co-actors.

Thirdly, if SoA in joint action is evaluated at a group level, not only self- and other's agency could determine SoA in joint action contexts, but also the extent to which the jointly produced action effects correspond to the intended joint action goal underlying the joint activity (Pacherie, 2012, 2014). Using 'joint' internal models to predict the expected consequences resulting from the combined action effects of self- and other executed actions could thus not only function to monitor progress towards the joint action goal and to trigger action adjustments in the interacting agents but also to monitor agency at the group level. Detecting discrepancies between predictions and the actual unfolding of joint actions at this level of action specification could generate agency cues that are relevant for agency assessment at the group level. This would imply, that SoA in joint action contexts depends not only on one's own performance and on the performance of one's co-actors but also on the combined performance of all engaged agents with respect to the desired outcome of the joint activity.

General challenges for accounts of SoA in joint action

From the outlined implications that the specificities of action specification and control in joint action bear for SoA in joint action contexts, some general challenges for accounts of SoA in joint action can be derived.

Firstly, we are confronted with a question concerning the agentive identity of people engaged in joint action. This question concerns the quality of an agent's agentive experience during a joint activity with others. A first possibility is that the agentive identity of someone engaged in a joint activity does not differ qualitatively from the case of acting in solitude, leaving the quality of his/her agentive experience to remain at the level of *self-agency*. This would imply, that SoA remains a purely egocentric property of human experience, even in the case of joint action, that is exclusively tight to action specification and control processes underlying individual action execution. However, as we have seen, action specification and control in joint action builds essentially on mechanisms and representations that extend purely egocentric processes and that bear specific implications for SoA. Moreover, if we consider the subjective phenomenology of acting together with others it is imposed on us that joint action bears a specific case with respect to agency. When I am rowing a boat together with my partner, for example, it is not only myself nor only my partner who is causing changes to the speed and the trajectory of the boat. Instead, *our actions together* or simply *we* are experienced as the common cause of how the boat is floating along. Based on such observations, philosopher have suggested that the agentive experiences during joint action may be better characterized as a sense of *joint agency* which is opposed against a basic sense of self-agency (Dokic, 2010; Pacherie, 2012, 2014; Seemann, 2009). Joint agency is characterized by these authors as "the perceptual sense that we are acting together" (Dokic, 2010, p. 40) resulting in a "sense of joint control" (Seeman, 2009, p.504) and, according to Pacherie (2012), is marked by "the sense that one's contribution to the joint outcome is commensurate to the contributions of one's coagents and that one's coordination relations with coagents are relatively symmetrical" (p. 375). Accordingly, a second possible form people's agentive identity could take in joint action contexts could be categorized as *joint agency*. This categorization can be differentiated even further as suggested by Pacherie (2012). Namely, in most situations in which people experience joint agency, they still have a pervasive experience of self-agency over their own contributions to the joint action as well as a solid grasp for the agentive situation of their co-actors. There might be situations however, in which the boundaries between self and others become so loose that people stop distinguishing between their own contributions to the joint activity and the contributions of co-actors. Situations like these may instead be characterized by a dissolution of self- and other awareness resulting in a complete merging of individual agency into the collective agency of the group. An example for such a situation can be found in testimonials of military drill operations or collective rituals such as communal dance practices (Pacherie, 2012)[1]. Pacherie (2012) categorizes this special sense of joint agency that is further characterized by a complete loss of self- and other-awareness as *we-agency,* and the more usual case in which people experience joint agency along with an intact sense of self-agency as *shared agency*.

Secondly, we are confronted with a question concerning the strength of SoA in joint action contexts. This question is concerned with the issue of what factors influence and determine the intensity of SoA we experience during joint action. How strong peoples SoA turns out when acting together with others depends firstly on the quality of their agentive experience classified along the categories outlined above. If SoA in joint action remains purely egocentric (i.e. reflects a sense of self-agency), the strength of SoA would be determined exclusively by the congruency between anticipated and observed consequences of self-executed actions. Under this assumption, co-actors' contributions to the joint activity could still alter the strength of SoA, but only indirectly, by affecting the predictability of self-produced action effects or by providing an alternative cause for observed action outcomes leading to causal discounting of self-authored contributions (Dewey et al., 2014). For the case of joint agency on the other side, the strength of SoA would not only be determined by purely egocentric processes tight to action specification and control of self-executed actions but also by the specificities of action specification and control characterizing coordinated joint action. As outlined above, these specificities allow the extension of agency monitoring to the actions of co-actors and to the level of the group as a whole. Under these circumstances, the intensity of SoA would depend not only on the congruency between anticipated and observed outcomes of self-executed actions but also on the matching of anticipated and observed outcomes of other-executed actions and on the accuracy of predicting jointly produced action effects (Pacherie, 2014). Thus, the

[1] To illustrate this point, Pacherie (2012) cites impressive reports by the military historian William H. McNeill who describes his subjective experiences during these practices in the book *Keeping Together in Time: Dance and Drill in Human History* (McNeill, 1995)

strength of the sense of joint agency would be directly affected by the performance of all co-actors in a joint activity and by their joint success in achieving the desired outcome of the joint activity.

As a third general challenge for accounts of SoA in joint action, we are confronted with open questions about the cues people use to sense agency in joint action contexts and how they get weighted and integrated. Could joint action contexts provide situations that change the relative weighting of sensorimotor, perceptual, and cognitive cues to agency? If SoA in joint action reflects a sense of joint rather than self-agency and agency is monitored at the group level, it would imply, that SoA in joint action must rely on performance cues that can be derived from one's own actions, the actions of co-actors as well as their combined action effects. This fact could point out an apparently minor role of sensorimotor cues and a more central role of perceptual and cognitive cues for SoA in joint action contexts. This is so because sensorimotor cues are by definition exclusively linked to self-executed actions, whereas perceptual and cognitive cues to agency rely on publicly available information (the perceptual unfolding of action effects arising in the joint activity and the overall performance with respect to the desired outcome of the joint activity) that allows to monitor agency with respect to self-produced action effects *and* with respect to other- and jointly produced action effects. Alternatively, though, sensorimotor cues to agency could also receive a relatively high weight in joint action contexts compared to perceptual and cognitive cues because they could function to establish and maintain a reliable discrimination between self- and other produced action effects that is beneficial in most joint action contexts.

Taken together, accounts of SoA in the context of joint action must address 1) how the agentive identity of people engaged in joint action is best characterized (as self-, shared- or we-agency), 2) how contributions of co-actors and the combined effects of self- and other executed actions affect the strength of SoA in joint action and 3) how joint action contexts affect the weighting and integration of sensorimotor, perceptual and cognitive cues to agency. In recent years, these issues got started to be addressed by a handful of empirical studies that will be reviewed next.

Empirical findings

Evidence for joint agency

First evidence that SoA in joint action reflects joint rather than self-agency is provided by studies that applied implicit measures of SoA in joint action contexts. Strother et al. (2010) and Obhi and Hall (2011) assessed SoA in joint task settings through intentional binding (IB), which refers to the phenomenon of compressed temporal perception of the interval between an action and its sensory effects, which is only observed if the action is intentional but not when the action is unintentional or if the action produced an unexpected or temporally non-contiguous sensory effect (Moore & Obhi, 2012). These studies showed that IB for auditory effects following a jointly produced action occurred to an equal extent in both co-actors involved in the task even if only one of the two co-actors initiated the action whereas the other only reactively joined or passively followed the action of the initiator. In contrast, explicit judgments of agency in both studies showed that only the initiator felt causally responsible for the auditory effects that resulted from the jointly produced action. The presence of IB in both agents could be interpreted as evidence for an automatic merging of the agentive identities of individuals engaged in a joint action into one unifying unit reflecting a "we" identity (Obhi & Hall, 2011). At least on a pre-reflective level, this merged agentive identity could lead people to experience agency over actions initiated by other co-actors which gets reflected in IB for the joining co-actor. On a reflective level on the other side, the two agents would remain their agentive identities as individuals which gets reflected in diverging explicit agency judgments. This would be in line with Pacheries' (2012) notion of shared agency suggested to underly most joint action contexts.

Indirect evidence for the existence of joint agency further comes from studies in which SoA of individuals engaged in a joint task was assessed through their explicit judgments of control over continuous joint actions. These studies focused in particular on the question, to what extent individual judgements of agency depend on factors that extended purely individual task performance. Therefore, Dewey et al. (2014) investigated the effect of sharing control over a moving object on people's individual judgments of control in a joint task. Participants in this study had to keep a cursor centred on a horizontally moving target by controlling the trajectory of the cursor with individual joysticks. In trials of the joint version of the task, the movement of the curser could either be influenced by participants' own joystick, their partner's joystick, random perturbations or any combination of the three. Assessment of participants' individual judgments of control over the trajectory of the cursor revealed that when contributions of both participants could have similar effects on the cursor, SoA was highest when the participants' own joystick had the only influence on the cursors' trajectory. Crucially, however, when contributions of both participants were complementary and control over ones' own joystick was not sufficient for successful joint task performance, SoA was highest when control was shared with the other participant. The latter finding indicates that the amount of agency felt in complementary joint actions is not exclusively determined by egocentric processes that match individual motor input to observed action effects but depends on the amount of control exhibited by the group as a whole. In a similar vein, van der Wel et al. (2012) showed that judgments of control in a joint task, in which participants coordinated their actions to rotate a pole along a fixed axis, were positively correlated with joint task performance of the dyad but not with the individual force deployed by each of the two actors. Adding up on this, results from another study by van der Wel (2015) showed that besides depending on successful joint task performance, judgements of control in a joint task, in which participants shared complementary control over the trajectory of a moving dot, were positively correlated with the smoothness of their own but also with the smoothness of their co-actors actions. Thus, not only participants individual performance but also the performance of co-actors determined the amount of SoA in the joint task. Taken together, these studies demonstrate that the strength of SoA in joint action is not exclusively determined by purely egocentric processes tight to action specification and control of self-executed actions. Crucially, the strength of SoA in joint action depends additionally on the performance of co-actors as well as the joint performance of the group with respect to the desired outcome of the joint activity, which is in line with the proposal that SoA in joint action reflects joint rather than self-agency.

Finally, direct evidence for the proposal that people engaged in joint action experience joint agency is provided by a study from Bolt et al. (2016). In this study, pairs of participants coordinated finger taps to jointly produce short sequences of sounds by tapping either sequentially or in alternation on touch-sensitive instruments in front of them. After every trial, participants rated the quality of their feelings of control on a scale that ranged from “shared control” to “independent control”. Across conditions, participants reported stronger feelings of shared as opposed to independent control over the reproduced sound sequence which indicates that participants experienced joint agency during the task.

Factors that strengthen joint agency

Based on the empirical evidence for joint agency outlined so far, recent studies started to investigate which factors alter the strength of this agentive experience. Therefore, the mentioned study by Bolt et al. (2016) assessed the effects of different structural conditions of joint actions on participants’ sense of joint agency. By manipulating the tapping condition (alternating vs. sequential) and the role of participants within the pair (leader started the sequence, follower joined in), the authors showed that joint agency is strengthened when both co-actors mutually had to coordinate their actions with respect to each other (stronger joint agency in alternating compared to sequential tapping condition) and that participants roles only had an effect on joint agency when coordination demands were asymmetrical (stronger joint agency for followers compared to leaders in sequential tapping condition). Thus, these results demonstrate that joint agency is influenced by the extent to which co-actors in a joint action must coordinate their actions with respect to each other. Building up on these findings, Bolt and Loehr (2017) showed further that joint agency is subject to the quality of one's co-actors performance in joint action contexts. In a similar task setting as in the Bolt et al. (2016) study, the authors manipulated the predictability of others' actions in the joint sequence reproduction task and showed that joint agency was stronger when the timing of others' actions was highly predictable even if controlled for participants own timing performance. This result indicates that joint agency rests strongly on the performance of others in a joint task and that people rely on predictions of co-actors' action effects to derive a sense of joint agency. Finally, Loehr (2018) investigated to what degree the joint task performance in a joint action determines the strength of joint agency. By applying the same task and rating scale as Bolt et al. (2016), the author showed that people reported stronger feelings of shared control as opposed to independent control when the overall task performance of the dyad turned out more successful. Accordingly, joint agency is further determined by the overall success of the group with respect to the desired outcome of the joint activity.

Cues to joint agency

As a critical next step for research on joint agency, the outlined findings must be linked to cognitive models explaining the generation of SoA in joint action contexts. This is to say that empirical studies addressing SoA in joint action should provide insights to the questions, what cues contribute to the generation of joint agency, how they get weighted in joint action contexts, and what mechanisms give rise to their formation and impact. Based on theoretical considerations, different possibilities to answer these questions where already outlined above, but so far only very few studies have addressed them directly. However, some of the already outlined studies provide hints elucidating these issues. Based on the assumption that agency monitoring at a group level must be based on performance cues that can get integrated across the actions carried out by oneself and by others, it was proposed that perceptual cues may receive a central role to monitor agency in joint action contexts because they can be derived from predictions of the perceptual unfolding of self-, other and jointly produced action effects alike. This suggestion receives evidence from the findings that the degree of agency felt in joint action contexts is based only partially on private sensorimotor processes underlying self-executed actions and depends additionally on the performance quality of others' action execution and the jointly produced action effects that can be monitored on a perceptual but not on a sensorimotor level (Bolt & Loehr, 2017; van der Wel, 2015; van der Wel et al., 2012). This would stress an important role of internal predictions of the sensory effects unfolding in joint action contexts on a perceptual level of action specification and control.

On the other side, however, it was also pointed out that private sensorimotor cues may receive central importance in joint action contexts due to their informative value in establishing a reliable discrimination between self and other produced action effects. This suggestion is likely supported by some of the study findings outlined above. Especially when the action effects resulting from self and other executed actions are perceptually hard or impossible to distinguish, people seem to rely strongly on private sensorimotor cues to sense agency in joint action contexts, potentially to hold contributions of self and others successfully apart (Dewey et al., 2014). Moreover, as in most complementary joint action contexts, the sense of joint agency is established along with an intact sense of self-agency over ones individual contributions to the joint activity and thus may be best characterized as a sense of shared agency (Pacherie, 2012), private sensorimotor cues should still have a reliable effect on SoA in joint action contexts. This proposal is supported by the data of Dewey et al. (2014), who showed that although judgments of agency in their joint task relied heavily on successful joint task performance, the contingency of perceptual changes on self-executed actions (visuomotor coupling) was still a reliable predictor for the strength of SoA in the task. This finding is further supported by a recent study of Le Bars et al. (2020). The authors had pairs of participants to coordinate keypresses to move a cursor to a target on a computer screen and manipulated motor fluency of the joint action by applying random deviations on the cursor's trajectory. After reaching the target, participants rated how much they had felt *individually* and how much they had felt *together* to be in control of the cursor's movement. The results revealed that low motor fluency of self-issued actions reduced both judgments of self-control and judgments of joint control, which points out the importance of sensorimotor cues for both self-agency and joint agency.

Finally, there is so far only one study that investigated the impact of external information and cognitive cues on the sense of joint agency. In the study by Loehr (2018) outlined above, the author investigated to what extend successful joint task performance alters the strength of joint agency. Crucially, in some trials, instead of relying only on internal performance cues, participants received also external feedback about their joint task performance. Results showed that the positive relationship between successful joint task performance and the amount of joint agency was even stronger when participants could rely on additional external cues about their performance. This finding indicates that external performance cues that were presented after the completed execution of the joint action had a reliable impact on people's sense of joint agency. Accordingly, besides relying on online performance monitoring of joint action execution, joint agency can be subject to information presented subsequently to the completion of a joint activity. This finding can only be accounted for if one assumes that joint agency relies in some part on a post-hoc matching of the observed outcome of a joint action with the distal joint action goal. Furthermore, Loehr (2018) suggests that the enhanced influence of successful joint task performance on the sense of joint agency is best explained through the relative high salience of this factor in trials in which participants received additional external feedback on their performance. Thus, it is pointed out that cues to joint agency may get dynamically weighted based on their saliency in the given context.

Summary

Based on the theoretical considerations and empirical findings that have been outlined in this section, we can draw an interim conclusion about the constitution of SoA in joint action contexts. In most joint action contexts, SoA does not reflect a purely egocentric property of human experience but depends significantly on action specification and control processes that extend beyond self-executed actions by also incorporating action execution by others as well as their combined consequences. Along with phenomenological descriptions of joint action, this indicates that SoA in joint action contexts is best characterized as joint rather than self-agency which is further supported by a growing body of empirical evidence. Future research on joint agency must now explain what the cognitive mechanisms are that give rise to this specific agentive experience during joint action and what cues underly its formation and alteration. Existing evidence on this issue indicates, that joint agency is subject to sensorimotor, perceptual, and cognitive cues to agency, but little is known about how these different cues get weighted and integrated to form specific experiences of joint agency in different joint action contexts.

1.3. The present study: Cues to joint agency

Taking the previously outlined issues and interim conclusions as a point of departure, we now turn to the empirical part of this thesis. As shall became clear, for a better understanding of the phenomena of joint agency it is crucial to pinpoint how the specific action specification and control processes operating during joint action yield different cues to joint agency and how these cues get integrated in different joint action contexts to generate specific experiences of joint agency. Therefore, the present study aims at extending our knowledge about the constitution of joint agency by investigating the impact and relative weighting of sensorimotor, perceptual, and cognitive cues to joint agency in different joint action contexts.

Research question

Building up on the assumption that SoA in joint action relies on a multiplicity of cues that get dynamically weighted and integrated based on their reliability in a given situation, it is assumed that the weighting of sensorimotor, perceptual and cognitive cues during joint action depends on the specific context of the joint activity. In joint action contexts that are marked by strong feelings of joint agency, people will evaluate agency at the level of the group as a whole and thus should rely predominantly on cues that allow to monitor agency at the group level. This suggests a potentially minor role of sensorimotor cues to agency as they are only available for self-executed actions but not for the actions of co-actors nor their combined effects. As perceptual cues to agency on the other side are publicly available, they allow to monitor the unfolding of self-, other, and jointly produced action effects alike and may receive a central role in these situations accordingly. In joint action contexts in which joint agency is weak instead, agency monitoring is focused mainly on individual contributions to the joint task. Accordingly, people should rely predominantly on egocentric cues in these situations which calls for a strong influence of private sensorimotor cues and a weaker influence of ambiguous perceptual cues to agency.

Based on this rationale it is asked whether different joint action contexts that alter the strength of joint agency are marked by a specific exploitation of available cues to agency. In particular, it is investigated if the balance between private sensorimotor cues and publicly available perceptual cues is shifted in joint action contexts that are known to elicit stronger feelings of joint agency. Furthermore, it is explored to which extend cognitive expectations can overrule reliable information provided by sensorimotor and perceptual cues and if their influence is dependent on specific conditions of the joint action.

Experimental approach

To approach these questions, an existing experimental paradigm that allows to differentiate the impact of sensorimotor, perceptual, and cognitive cues to agency (Knoblich & Repp, 2009) was adopted to a joint task setting. The joint task comprised a sequence reproduction task in which pairs of participants had to coordinate actions to reproduce the tempo of a short metronome sound sequence as accurately as possible by tapping on a touch-sensible device in front of them. Participants issued their individual taps either in alternation or sequentially so that each participant was responsible for half of the taps that made up the sequence. While tapping, participants heard sounds that were either triggered by their finger taps or controlled by a computer. Thus, the timing of the sounds heard during tapping could

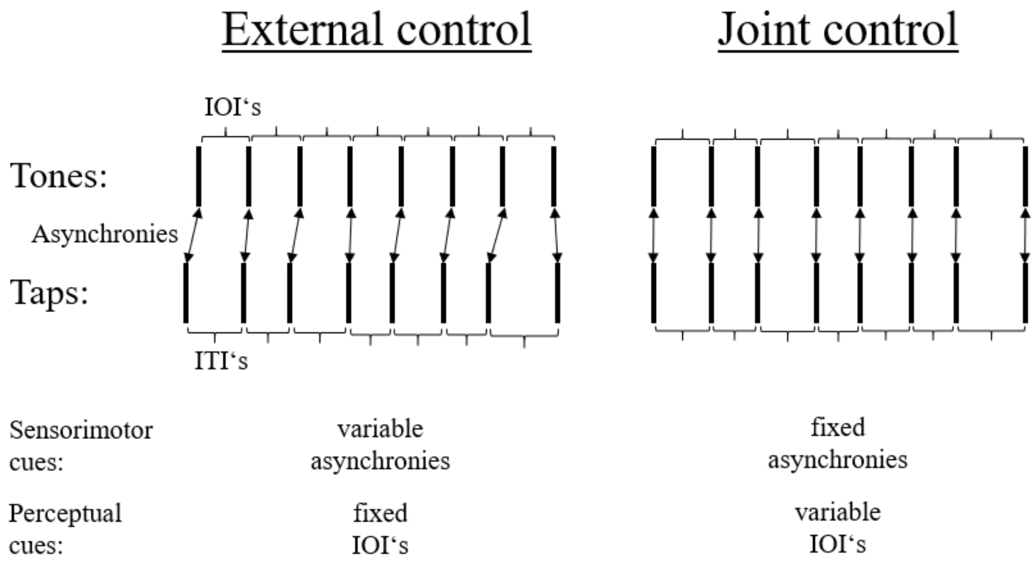

Figure 1. Schematic illustration of agency cues in the described task. IOI refers to inter onset interval between tones, ITI refers to inter tap intervals.

either be jointly controlled by the dyad (joined control) or by an external source respectively (external control). After the reproduction of each sequence, participants were asked to report whether the sounds that occurred during tapping had been controlled by them (i.e. joint control of the sound sequence) or by the computer (i.e. external control of the sound sequence).

Distinguishing successfully between joint and external control in this task is possible based on two principle cues to agency that are linked to participants' monitoring of their tapping performance (see Fig. 1). First, asynchronies between taps and tones provide private sensorimotor cues to agency in this task. As SoA is assumed to rely in part on accurate predictions of the sensory consequences of self-executed actions based on ones' own motor commands, detecting unexpected asynchronies between a tap and a tone would inform the participant that the tone was likely not caused by one's own action but by an external source. Crucially, unexpected asynchronies between taps and tones can only occur when the tones are controlled by the computer because asynchronies in this condition can vary from tap to tap due to human movement variability. When tones are triggered by participants' finger taps instead, asynchronies are fixed at a small interval reflecting only a short processing delay between tap and subsequent tone. Accordingly, participants could rely on the detection of sensorimotor discrepancies to distinguish joint from external control trials. Secondly, temporal variability of the intervals between tones provides perceptual cues to agency in this task. In computer-controlled trials, these intervals are fixed at the programmed duration from one tone to another and thus don't vary over the curse of the sequence. In trials in which the sounds are jointly controlled by the two participants instead, these intervals vary over the curse of the sequence due to the imperfection of participants' action timing. Thus, detecting temporal variability in the sound sequence informs participants that the sound sequence was likely produced by them and not by the computer. Accordingly, participants could also distinguish joint from external control trials by monitoring how the purely perceptual events in the task (i.e. the tones) unfold over time. By analysing participants discrimination ability and the extent of asynchronies and timing variability in the trials as a function of participants' responses, one can draw independent conclusions about the respective efficacy of sensorimotor and perceptual cues to agency (cf. Knoblich & Repp, 2009). To some extent, the paradigm also allows to draw conclusions about the role of cognitive cues to agency in the task. In two studies, using the outlined paradigm in a solo task setting, Knoblich and Repp (2007, 2009) observed that participants showed a general tendency towards reporting that they and not the external source had control over the tone sequence, which may point to a general cognitive bias towards feeling in control of external sensory events when acting. Thus, by analysing participants response bias, one can draw partial conclusions about the extent cognitive expectations ruled out more reliable information provided by sensorimotor and perceptual cues.

As it was aimed at investigating how sensorimotor, perceptual and cognitive cues get weighted and integrated in different joint action contexts that alter the strength of joint agency, the height of *coordination demands* arising for the participants in the task was manipulated by means of the two tapping conditions (alternating tapping where both participants mutually have to coordinate their actions with that of the other participant vs. sequential tapping where only the second participant has to coordinate his/her actions with that of the first participant). Furthermore, participants' *roles* in the task (leader who started the sequence vs. follower who joined in) varied systematically across different blocks in the task. These two manipulations were adopted from the study by Bolt et al. (2016), who showed that higher coordination demands lead to stronger feelings of joint agency whereas followers report stronger feelings of joint agency compared to leaders when coordination demands are low. Thus, manipulating coordination demands (high: alternating tapping vs. low: sequential tapping) and participants' role in the task (leader vs. follower) aimed at eliciting differences in the strength of joined agency between the resulting joint action conditions.

Hypotheses and predictions

Based on the findings by Bolt et al. (2016), it is hypothesized that higher coordination demands in the task will elicit stronger feelings of joint as opposed to individual agency in participants. Furthermore, participants' role in the task is hypothesized to affect joint agency only when coordination demands are low so that followers will experience stronger sense of joint agency compared to leaders under low coordination demands. These hypotheses get reflected in the predictions that participants will report stronger feelings of shared as opposed to individual control over the reproduction sequence when tapping in alternation compared to when tapping sequentially. Furthermore, participants are expected to report stronger feelings of shared as opposed to individual control in the sequential tapping condition when they have the role of followers.

Crucial for the stated research question, it is further hypothesized that the expected differences in the strength of joint agency will be reflected in different exploitations of available cues to agency in the task. Specifically, it is expected, that stronger feelings of joint as opposed to individual agency will find expression in a dominant influence of perceptual cues and a minor influence of sensorimotor cues to sense agency in the outlined task. In contrast, weaker feelings of joint agency are expected to find expression in a stronger influence of sensorimotor cues and a weaker influence of perceptual cues to sense agency in the task. Accordingly, it is predicted that people will rely in great part on the temporal variability of tones to inform their agency judgments when tapping in alternation whereas the information stemming from asynchronies between taps and tones will be less regarded in this condition. In contrast, when tapping sequentially, people will rely in great part on asynchronies between taps and tones to inform their agency judgments and to a smaller extent on the temporal variability of tones.

2. Methods

2.1. Participants

12 randomly composed pairs of adult participants took part in the study. Participants were recruited via an online research participation system of the Central European University in Budapest, Hungary. All participants provided written informed consent and received gift vouchers for compensation in line with the ethical approval of the study granted by the United Ethical Review Committee for Research in Psychology (EPKEB) in Hungary. One pair was excluded from data analysis because participants did not fulfil minimal task requirements (see below for details). The final sample consisted of 11 female and 11 male participants (mean age = 25.6, *SD* = 3.9) divided into two purely female pairs, two purely male pairs, and seven pairs of mixed gender.

2.2. Apparatus and material

Participants sat next to each other on the same side of a table divided by an occluder that prevented participants from seeing each other. Participants issued finger taps on individual IPad Pros in front of them that displayed a user interface via the IOS app MIRA 1.2.1 that was connected to a custom patch created in Max MSP 8 running on a Mac computer. The MIRA interface displayed the respective condition of each trial and a designated area where participants were supposed to issue their finger taps. The interface was also used to record participants' judgments after each trial. The Max MSP patch was controlled and monitored by the experimenter who sat behind another occluder outside the view of participants and served to present tones and to record the timing of participants' taps. Tones were presented via speakers facing the two participants and represented a build-in digital sound file ("snare 01.wav") from the Max MSP software. The task setup is depicted in Fig. 2 A.

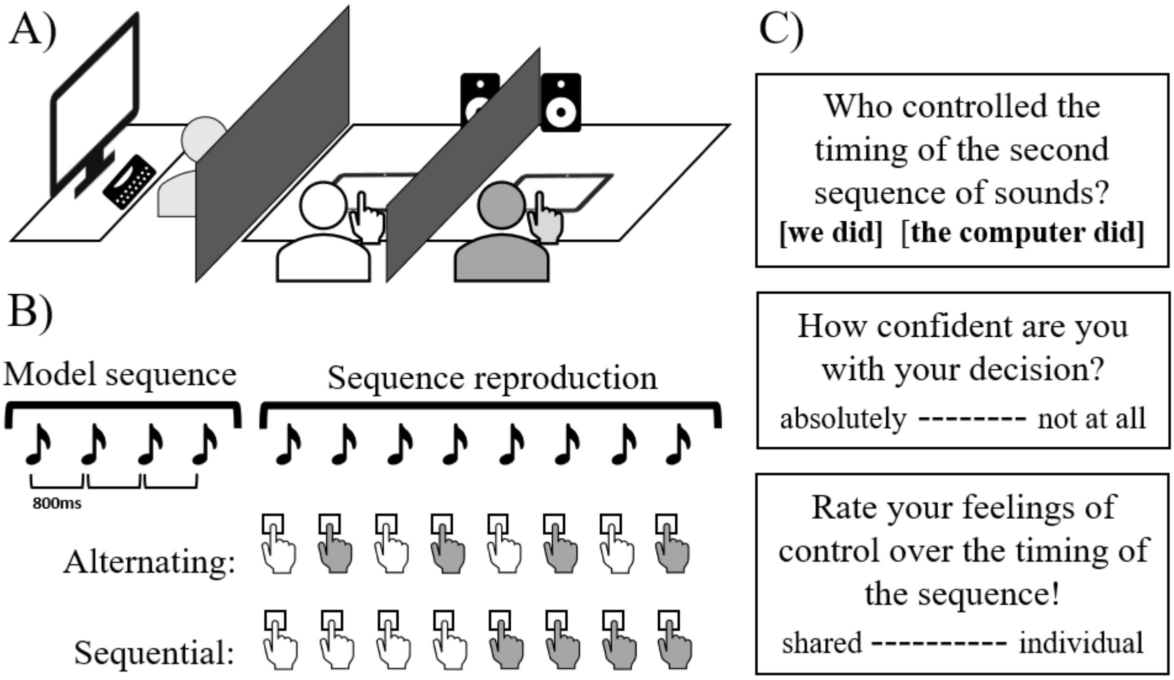

Figure 2. A) Schematic illustration of the task setup. B) Schematic illustration of the sequence reproduction task and the two tapping conditions. C) Formulation of the items and response categories presented at the end of each test trial.

2.3. Task description and study design

Participants were instructed to reproduce the tempo of a short metronome model sequence that consisted of four isochronous snare tones with an inter onset interval (IOI) of 800ms together with their partner as accurately as possible by issuing taps with the index finger of their strong hand on the IPads in front of them. Each reproduction sequence consisted of eight taps in total divided into four taps per participants so that each participant was responsible for half of the reproduction sequence (see Fig. 2 B).

The task comprised a 2 (tapping condition: alternating vs. sequential) by 2 (role: leader vs. follower) by 2 (control mode: joint control vs. external control) within-subjects design. In half of the trials, participants issued finger taps in alternation with each other so that participants took turns issuing their taps (e.g. ABABABAB, where A and B refer to each partner respectively). In the other half of the trials, participants tapped sequentially so that one partner produced the first four taps and the other produced the remaining four taps (e.g. AAAABBBB). Both partners hold the role of leaders who started the sequence in half of the trials and that of followers who joined in in the other half of the trials. While tapping, participants heard a total of eight snare tones. In 50% of the trials, the tones were always contingent on participants finger taps so that participants' taps controlled the timing of the tones. In the other 50% of the trials, the timing of the tones was controlled by the computer that, triggered by the first tap of the participant who started the sequence, produced the eight tones with a regular IOI of 800ms and thus perfectly matched the tempo of the model sequence. The respective tapping condition and distribution of roles were announced before each trial. Crucially, control mode of each trial was unknown for participants.

After the reproduction of each sequence, participants were asked to indicate whether the timing of the tones heard during tapping had been controlled by them or by the computer and rated how confident they were with their respective decision. Furthermore, participants rated their sense of joint agency on a scale that ranged from shared to individual control. Fig. 2 C displays the precise formulation of the questions and the respective response options.

2.4. Procedure

The experiment was conducted in the Music Lab of the Social Mind Center at Central European University in Budapest, Hungary. Upon arrival at the lab, participants gave written informed consent for participating in the experiment and were randomly assigned to one of the two seating positions. The experiment started with a practice phase in which participants received standardized instructions on their IPads and got used to the technical setup and task procedure.

Practice blocks

In a first practice block, participants completed 12 trials in which the timing of the tones during sequence reproduction was controlled by the dyad (i.e. joint control). The trials comprised 4 trials for each combination of tapping condition and role distribution whose order resembled the order of the subsequent test blocks (see below). Each trial was started by the experimenter. Participants were instructed to listen to the short model sequence and, after a brief pause, to reproduce its tempo as accurately as possible by tapping according to the respective condition. After each sequence reproduction participants received feedback about their timing performance: If the mean inter tap interval (ITI) of the reproduction sequence was within ± 10% of the model IOI (800ms), “Good!” was displayed on participants IPads, if not, the feedback was “Too fast!” or “Too slow!” respectively.

In a second practice block, participants completed 12 trials in which the timing of the tones heard during sequence reproduction was controlled by the computer (i.e. external control). Again, the trials comprised 4 trials in each combination of tapping condition and role distribution, ordered as in the previous practice block. Again, participants were instructed to listen to the short model sequence and, after a brief pause, to reproduce its tempo as accurately as possible by tapping according to the respective condition, this time in synchrony with the computer-controlled tones. Feedback in these trials was given based on the asynchronies between participants’ taps and computer-controlled tones: If the maximal asynchrony was less than 20% of the model IOI, the feedback was “Good!”, otherwise the feedback was “Not accurate enough!”.

In a last practice block, participants completed 4 trials reflecting each combination of tapping conditions and role distribution in which the control mode of the tones during sequence reproduction was randomized and unknown to participants. Instructions were the same as described above but no feedback about participants tapping performance was given anymore. Instead, after sequence reproduction, each participant was asked to indicate who they felt had “controlled the timing of the second sequence of tones” by tapping on one of two buttons displaying “we did” and “the computer did” in a separate tab of the MIRA interface. Furthermore, participants indicated how confident they felt with their preceding decision by moving a horizontal slider on a visual analogue scale that ranged from 0 to 100 with the respective endpoint labels “not at all” and “absolutely”. Finally, participants were asked to “Rate your feelings of control over the timing of the second sequence of tones” on a similar visual analogue scale that ranged from “shared control” to “individual control”. After participants’ responses were recorded, the experimenter started the next trial. After completion of the third training block, participants had a last chance to ask questions about the task procedure and to report unclarities. Subsequently, the experiment continued with the actual test trials.

Test blocks

The procedure of the subsequent test trials was the same as for the third practice block just described. Participants completed a total of 96 test trials, 24 trials per tapping condition both as leaders and as followers of which 12 represented trials in which the timing of tones was controlled by the dyad and 12 in which the timing of tones was controlled by the computer. The trials were split into 8 blocks of 12 trials. Tapping condition and role distribution were hold constant in each block so that each combination of the two factors occurred twice throughout test blocks. Blocks switched between alternating and sequential tapping condition and their order was counterbalanced across pairs. Who took the role as a leader in the first block (the person sitting on the right or at the left side of the table) was counterbalanced across pairs. The person who was the leader for the first block became the follower for the second and third block and took the role as leader again in the fourth block. This order of role distribution was repeated for the remaining four test blocks. Control mode varied randomly from trial to trial but was balanced in each block so that 6 of the 12 trials per block reflected joint and the other 6 external control trials.

The respective tapping condition and role distribution for each block were announced by the experimenter and were displayed throughout the block on participants IPads. The experimenter started each test trial individually and monitored participants' responses throughout the whole experiment outside their view. The end of each block was announced by the experimenter after which participants had the chance to make a small pause. After completion of the 8 test blocks, participants were debriefed and received gift vouchers according to the duration of the experiment. The experiment lasted approximately one hour.

2.5. Measures and data analysis

Joint agency ratings

To assess participants sense of joint agency during the different task conditions, for each combination of tapping condition and role distribution respectively, the reported extent of shared as opposed to individual control felt during sequence reproduction was averaged across all trials in which participants indicated that the tones heard during sequence reproduction had been controlled by the dyad. Mean agency ratings significantly below 50[2], were considered as reflecting stronger feelings of shared as opposed to individual control.

[2] For all inference statistical analyses reported, the significance level was set to .05.

Discrimination sensitivity and response bias

How well participants were able to distinguish between joint and external control mode and whether participants showed a general tendency to respond one way or the other was assessed through measures from signal detection theory. Based on participants responses who they felt had been in control over the tones heard during sequence reproduction and the actual control mode in each trial, proportions of hits (responding “we did” in joint control trials) and false alarms (reporting “we did” in external control trials) were obtained for each participant in each tapping condition respectively. Based on these proportions, the sensitivity index *d’* (*d’* = *z*(hit rate) – *z*(false alarm rate); quantifying participants ability to distinguish joint from external control mode) and the bias parameter *c* (*c* = -½[*z*(hit rate) + *z*(false alarm rate)]; quantifying the propensity of participants to respond “we did” or “the computer did”) were calculated, again for each participant in each tapping condition respectively.

Confidence ratings

Participants’ confidence ratings for their decision to report “we did” or “the computer did” respectively were averaged for each participant across all trials as a function of tapping condition and respective response.

Tapping performance

In each trial, the timing of participants taps and that of the occurring tones was recorded and served to calculate the IOI’s between the tones that accompanied participants taps during sequence reproduction as well as the occurring asynchronies between participants taps and tones. Note again that during external control trials the IOI’s between tones were fixed at the programmed duration of 800ms and perfectly matched that of the model sequence whereas during joint control trials, IOI’s between tones reflected participants ITI’s that could vary throughout the sequence (cf. Fig. 1). On the other side, during joint control trials asynchronies between taps and tones were fixed at a minimal interval that reflected only a short processing delay of several milliseconds whereas during external control, asynchronies between taps and tones could vary in direction and magnitude (cf. Fig. 1).

For each trial, the absolute difference between the mean reproduction IOI and the model IOI (capturing the mean tempo difference between the model and reproduction tone sequence) and the standard deviation of the IOI’s during sequence reproduction (capturing temporal variability of the tones) were calculated and served as dependent measures for the subsequent analysis of the efficacy of perceptual cues to agency in the task. The mean and standard deviation of the absolute asynchronies between taps and tones in each trial served as dependent measures for the subsequent analysis of the efficacy of sensorimotor cues to agency in the task.

Before analysing results, each participant's data was screened to eliminate all trials with missing or extra taps, all joint control trials in which the mean IOI of the tones during sequence reproduction deviated by more than ± 100ms from the model IOI or in which the standard deviation of the IOI's exceeded 100ms, and all external control trials in which the mean or the standard deviation of the absolute asynchrony between taps and tones exceeded 100ms. For each participant, error rates were calculated based on the loss of trials due to the outlined criteria. Pairs containing participants with an error rate grater than 50% were excluded entirely from subsequent analysis which effected one of the twelve pairs. Error rates of the remaining participants ranged from 2% to 39%.

3. Results

3.1. Joint agency ratings

Fig. 3 shows the mean joint agency ratings as a function of tapping condition and role. Overall, participants reported stronger feelings of shared as opposed to individual control (M = 34.69, 95% CI [29.79, 39.59]), $t(87) = -6.21$, $p < .001$. However, a 2 (tapping condition: alternating vs. sequential) x 2 (role: leader vs. follower) repeated measure ANOVA revealed no differences in mean joint agency ratings between tapping conditions, $F(1,21) < 1$, nor between roles, $F(1,21) = 1.22$, $p = .28$, and the interaction effect was also far from statistical significance, $F(1,21) < 1$.

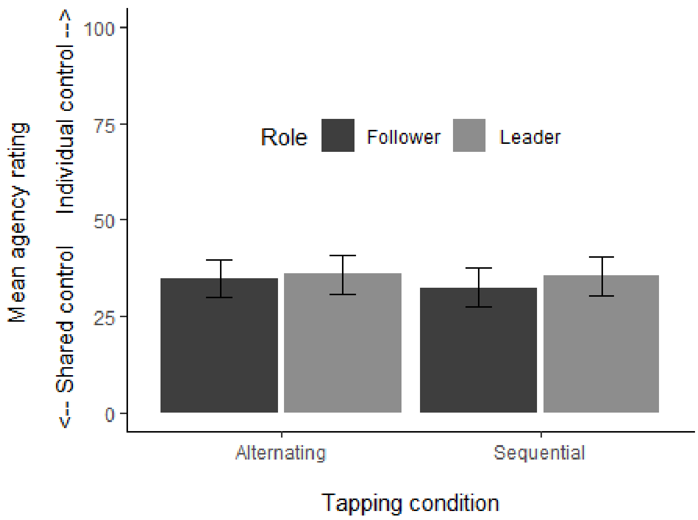

Figure 3. Mean joint agency ratings as a function of tapping condition and role. Error bars represent standard errors.

3.2. Discrimination sensitivity and response bias

Fig. 4A shows the mean *d'* values for each tapping condition. A one-way repeated measures ANOVA revealed no difference in the ability to discriminate joint from external control between the two tapping conditions, $F(1,21) < 1$. The mean bias indices are shown in Fig. 4B. In both conditions the bias was significantly larger than zero, $t(21) = 8.30$, $p < .001$ for the alternating tapping condition, $t(21) = 4.08$, $p = .001$ for the sequential tapping condition. However, a one-way repeated measures ANOVA on the data indicated no significant difference between the two tapping conditions, $F(1,21) = 1.29$, $p = .29$.

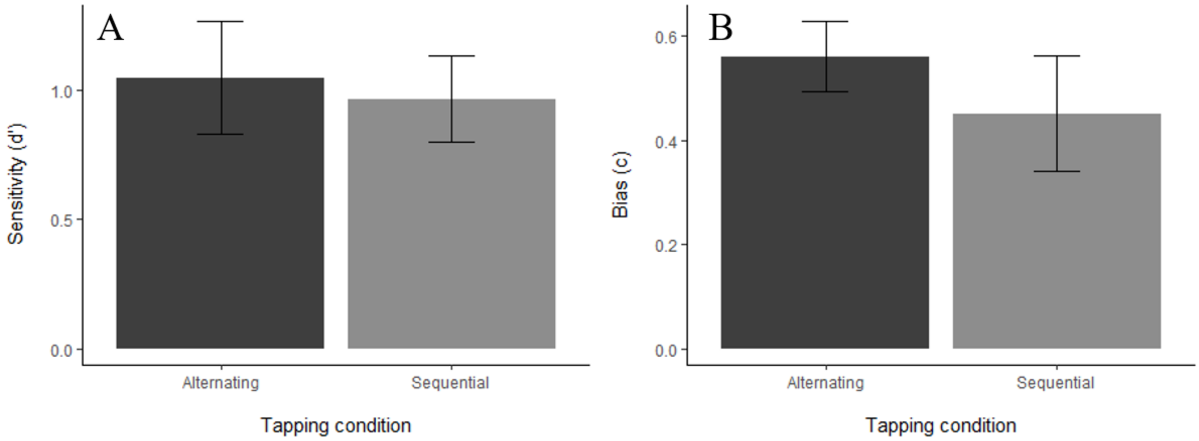

Figure 4. A) Mean sensitivity index (*d'*) in the two tapping conditions. B) Mean bias parameter (*c*) in the two tapping conditions (positive values indicate a tendency to report joint rather than external control). Error bars represent standard errors.

3.3. Confidence ratings

Fig. 5 shows the mean confidence ratings of participants in their response who they have felt to be in control of the tones heard during sequence reproduction as a function of the respective response and tapping condition. A 2 (tapping condition: alternating vs. sequential) x 2 (response: “we did” vs. “the computer did”) repeated measures ANOVA revealed a significant main effect of response, $F(1,21) = 8.65$, $p = .008$, so that participants were more confident when reporting joint control ($M = 74.9$, 95% CI [69.8, 80.0]) than when reporting external control (M = 66.3, 95% CI [62.2, 70.5]). The main effect of tapping condition was not significant, $F(1,21) < 1$. Furthermore, there was a significant interaction between both factors, $F(1,21) = 19.5$, $p < .001$. Separate one-way ANOVAs for both tapping conditions showed the effect of response to be significant in the alternating tapping condition, $F(1,21) = 16.2$, $p < .001$, but not in the sequential tapping condition $F(1,21) = 1.77$, $p = .19$.

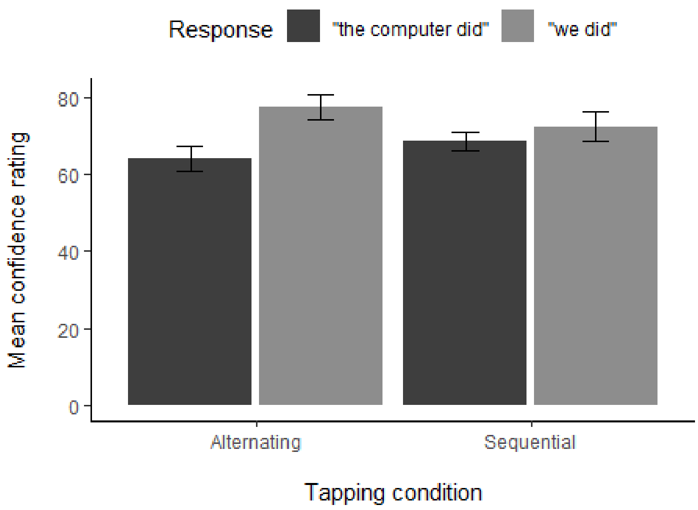

Figure 5. Mean response confidence ratings in the two tapping conditions, contingent on the respective response of participants. Error bars represent standard errors.

3.4. Tapping performance

Error rates

Fig. 6 shows the mean error rates as a function of tapping condition and role. A 2 (tapping condition: alternating vs. sequential) x 2 (role: leader vs. follower) repeated measures ANOVA showed a significant main effect of tapping condition, $F(1,21) = 27.7$, $p < .001$, with higher error rates in the alternating ($M = 26\%$, 95% CI [20%, 32%]) than in the sequential tapping condition ($M = 6.7\%$, 95% CI [4.3%, 9.2%]). The main effect of role was also significant, $F(1,21) = 15.6$, $p < .001$, with higher error rates for follower ($M = 20\%$, 95% CI [14%, 26%]) compared to leader ($M = 13\%$, 95% CI [7.9%, 17%]. The interaction effect of the two factors was not significant, $F(1,21) < 1$.

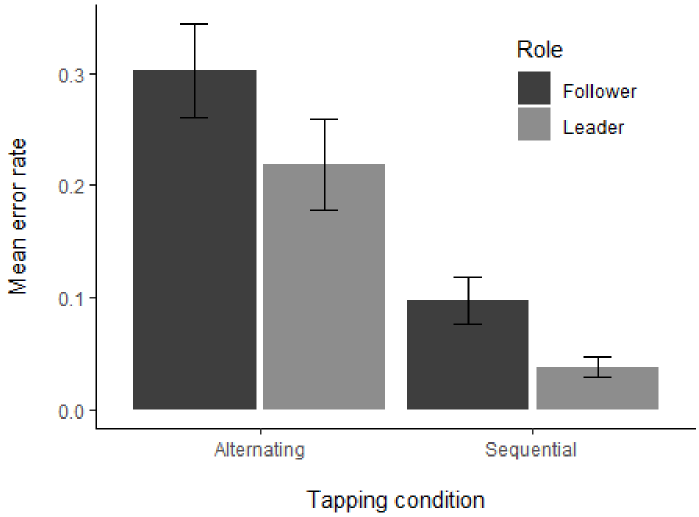

Figure 6. Mean error rates (percentage of trial loss due to wrong or inaccurate tapping) by tapping condition and role. Error bars represent standard errors

Efficacy of perceptual and sensorimotor cues to agency

To examine which cues participants presumably relied on in making their responses to the question who they had felt to be in control of the tones heard during sequence reproduction, participants tapping performance in each trial was set in relation to their respective response.

Fig. 7 shows two perceptual cues indicating joint control of the tones heard during sequence reproduction: The absolute difference between the mean reproduction IOI of a trial and the model IOI (i.e. the tempo difference between reproduction sequence and model sequence; Fig. 7A) and the standard deviation of the reproduction IOI's in a trial (i.e. temporal

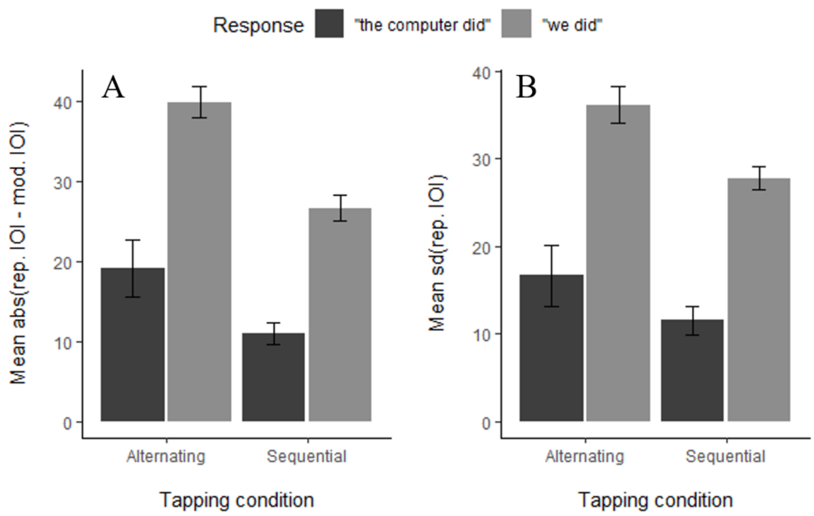

Figure 7. Response locked analysis of perceptual cues to agency in the task. A) Mean absolute difference between reproduction IOI and model IOI in each tapping condition contingent in participants' responses. B) Mean standard deviation of the reproduction IOI`s in each tapping condition contingent on participants' responses. Error bars represent standard errors.

variability of the reproduction tone sequence, Fig. 7B). The means of these variables are shown for each tapping condition respectively, contingent on participants' responses. It is evident that both cues were more pronounced when participants responded that the tones heard during sequence reproduction had been controlled by them instead of the computer. For the data in Fig. 7A, a 2 x 2 repeated measures ANOVA confirmed this by revealing a significant main effect of response, $F(1,21) = 37.1$, $p < .001$, that reflected larger mean tempo differences between model and reproduction when participants reported "we did" (M = 33.3ms, 95% CI [30.0, 36.6]) compared to trials with "the computer did" responses (M = 15.1ms, 95% CI [11.1, 19.1]). The main effect of tapping condition was also significant, $F(1,21) = 45.2$, $p < .001$, with larger mean tempo differences between model and reproduction in the alternating (M = 29.5ms, 95% CI [24.4, 34.7]) than in the sequential tapping condition (M = 18.7ms, 95% CI [15.6, 22.1]). Crucially, however, the main effect of response was not found to be moderated by the two tapping conditions as revealed by a non-significant interaction effect of the two factors, $F(1,21) = 1.50$, $p = .86$. A similar ANOVA on the data in Figure 7B revealed a complementary pattern of results with a significant main effect of response, $F(1,21) = 33.1$, p < .001, showing greater temporal variability of reproduction IOI's in trials in which participants responded "we did" (M = 32.0, 95% CI [29.2, 34.8]) compared to trials with "the computer did" responses (M = 14.1, 95% CI [10.2, 18.0]), a significant main effect of tapping condition, $F(1,21) = 15.2$, p < .001, with greater temporal variability of the reproduction IOI's in the alternating (M = 26.4ms, 95% CI [21.4, 31.5]) than in the sequential tapping condition (M = 19.7ms, 95% CI [16.5, 22.9]), and a non-significant interaction effect of both factors, $F(1,21) < 1$.

Fig. 8 shows two sensorimotor cues indicating external control of the tones heard during sequence reproduction: The mean absolute asynchronies between taps and tones (Fig. 8A) and the standard deviation of the absolute asynchronies (Fig. 8B). The means of these variables are shown again for each tapping condition respectively, contingent on participants' responses. It is apparent that both cues were more pronounced in trials in which participants responded "the computer did" irrespective of the specific respective rapping condition. This was confirmed by two 2 x 2 repeated-measures ANOVA on the data in Fig. 8A and Fig 8B respectively. The mean absolute asynchronies between taps and tones were larger in trials in which participants responded "the computer did" (M = 32.2ms, 95% CI [28.8ms, 35.6ms]) compared to trials in which participants responded "we did" (M = 16.4ms, 95% CI [14.1ms, 18.8ms]), $F(1,21) = 43.6$, $p < .001$. The mean absolute asynchronies were also larger in the alternating (M = 28.3ms, 95% CI [24.0ms, 32.6ms]) compared to the sequential tapping condition (M = 20.4ms, 95% CI [17.6ms, 23.1ms]), $F(1,21) = 31.1$, $p < .001$. Crucially, the interaction effect of both factors was

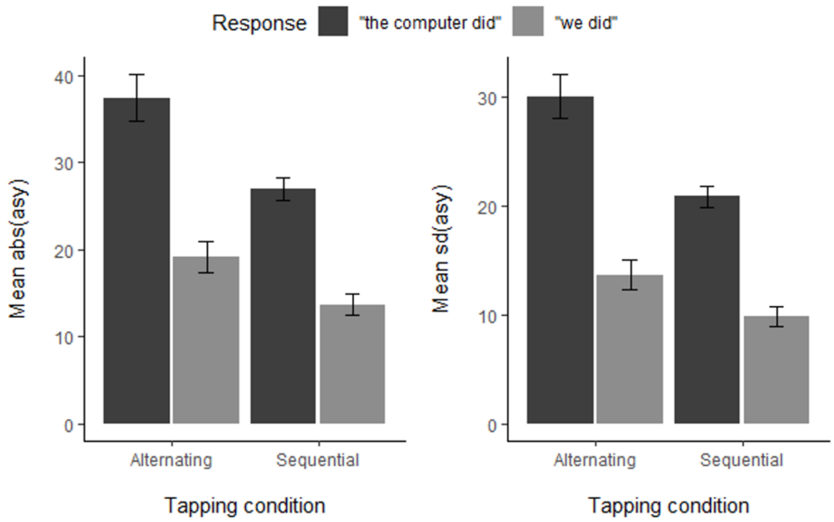

Figure 8. Response locked analysis of sensorimotor cues to agency in the task. A) Mean absolute asynchronies between taps and tones in each tapping condition contingent on participants' responses. B) Mean standard deviation of asynchronies in each tapping condition contingent on participants' responses. Error bars represent standard errors.

far from being significant, $F(1,21) = 1.93$, $p = .66$. The same pattern of results emerged also for the similar analysis of the standard deviation of the absolute asynchronies. Asynchronies showed more variability in trials in which participants responded "the computer did" ($M = 25.5$, 95% CI [22.8, 28.1]) compared to trials in which the response was "we did" ($M = 11.7$, 95% CI [10.0, 13.5]), $F(1,21) = 66.5$, $p < .001$. Asynchronies varied also more in the alternating tapping condition ($M = 21.9$, 95% CI [18.3, 25.4]) than in the sequential tapping condition ($M = 15.4$, 95% CI [13.2, 17.5]), $F(1,21) = 41.4$, $p < .001$. Again, the interaction effect of both factors was not significant, $F(1,21) = 2.96$, p = .37.

4. Discussion

4.1. Interpretation of results

Joint agency ratings

Overall, participants reported stronger feelings of shared as opposed to individual control during the task, which indicates that people do experience joint rather than mere individual agency in cooperative joint action as proposed by previous philosophical accounts (Pacherie, 2012; Seemann, 2009) and recent empirical studies (Bolt et al., 2016; Dewey et al., 2014; Obhi & Hall, 2011). Thus, being engaged in a cooperative activity with others leads people to experience a sense of joint or shared control over the unfolding actions and effects of the joint activity and extends action control and agency monitoring beyond purely individual action contributions. In contrast to previous findings (cf. Bolt et al., 2016), however, the sense of joint agency was not found to be affected by the height of coordination demands participants were facing during the task nor by their assigned roles. Instead, participants reported equally strong feelings of shared as opposed to individual control under high (alternating tapping condition) and low (sequential tapping condition) coordination demands and irrespective of their assigned role as leader or follower.

The results of the present study thus partly diverge from findings of previous studies that found joint agency to be enhanced when people face higher coordination demands and when they have the role of followers instead of leaders (Bolt et al., 2016). However, the reported findings must not be interpreted as a failed replication of these previous findings. Crucially, in the present study, participants were facing slightly different task demands than in the study by Bolt et al. (2016) that can be made accountable for the differing results. Namely, in the present study, besides reproducing the timing of the model sequence as accurately as possible by tapping in the respective conditions, participants were additionally required to monitor whether the tones heard during sequence reproduction were controlled by their actions or by an external source instead. In the study by Bolt et al. (2016) on the other side, the tones heard during sequence reproduction were always contingent on participants' finger taps and participants were only asked to report the amount of shared control experienced during the task. Crucially, the additional task demand in the present study imposes a different informative value of co-actors' contributions to the task. In the task setup by Bolt et al. (2016) monitoring of co-actors' actions was mainly important to sustain successful action coordination between each other, which was of increased necessity when participants faced high coordination demands or when they had the role of a follower instead of a leader. Thus, in Bolt et al.'s (2016) task setup, participants were more likely to take action contributions of their co-actors into account when facing high coordination demands or when having the role of a follower which may explain stronger feelings of joint agency in these task conditions. In the present study on the other side, monitoring the contributions of co-actors was of further importance for participants due to their epistemic value for distinguishing between joint and external control mode. Crucially, the informative value of co-actors' contributions with respect to examining control mode was given equally under high and low coordination demands and independent of role assignments. Thus, in the present study, participants were encouraged to take their co-actors action contributions into account and to regard them as commensurate to their own contributions, regardless of high or low coordination demands and role assignment which may explain the equally strong feelings of joint agency found across the different task conditions. This would imply that strong feelings of joint agency are not necessarily tight to joint action contexts in which participants mutually coordinate their actions with respect to each other. Instead, for a sense of joint agency to arise, it seems sufficient that people monitor the unfolding of their co-actors' actions with respect to agency for whatever reason, and it is likely that the strength of joint agency is determined by the extend people are prone to do so.

Critically for the purpose of the current study, the applied manipulations (high vs. low coordination demands; leader vs. follower) failed to elicit differences in the strength of joint agency within participants. As the main question behind the current study asked whether different joint action contexts that alter the strength of joint agency are marked by specific exploitations of agency cues, the present study turned out as being unable to answer this question ultimately. However, as participants did indeed experience joint agency across conditions, the further results of the present study are still able to shed light on the cues that gave rise to this specific agentive experience.

Discrimination sensitivity and response bias

Analysis of participants' ability to distinguish between control modes showed that discrimination between joint and external control was equally good under high and low coordination demands. This finding indicates that overall participants made equally effective use of available cues to agency irrespective of coordination demands.

Analysis of participants' response bias revealed that under both high and low coordination demands participants showed a strong tendency to report joint rather than external control. Thus, irrespective of coordination demands, participants were much more likely to experience the tones heard during sequence reproduction as controlled by them instead of the computer, although control mode was fully balanced across trials. This finding could be interpreted as reflecting a general cognitive bias to feel in control of external events when issuing congruent actions roughly at the same time (cf. Wegner, 2002) which could have led participants to disregard more reliable information stemming from sensorimotor and perceptual agency cues. A novel aspect of the present study would then be that this cognitive bias is not limited to individual action scenarios but extends to joint action contexts in the sense that people engaged in joint action tend to attribute control over external events to the interacting group. This would point out a strong influence of cognitive cues on the sense of joint agency. However, the finding of a bias towards joint control responses can be alternatively interpreted as resulting from a failure to detect sensorimotor discrepancies during external control trials (Knoblich & Repp, 2009). If participants used sensorimotor cues stemming from asynchronies between taps and tones to inform their responses, asynchronies may often have been too small to detect during external control trials leading participants to experience joint control instead. Another possibility is that the bias reflects an influence of perceptual cues. Crucially, detecting no tempo difference between model and reproduction tone sequence and no temporal variability of the tones heard during sequence reproduction were positive indicators for *external* control in the present task. Thus, if the timing of tones heard during sequence reproduction perfectly matched the timing of the model sequence, participants should have tended to report external instead of joint control. However, in such cases, the observed unfolding of the perceptual events (i.e. the observed timing of the tones heard during sequence reproduction) perfectly matched participants' proximal intention of reproducing the timing of the model sequence as accurately as possible. Thus, following perceptual accounts of SoA (Jeannerod, 2009; Pacherie, 2008), participants should experience a strong sense of joint agency in trials in which the timing of tones heard during sequence reproduction perfectly matched that of the model sequence which would lead participants to report joint control during external control trials. This possibility would also be in line with the finding that more successful joint task performance (perfectly matching the tempo of the model sequence in the present study) strengthens the sense of joint agency (Loehr, 2018).

Taken together, analysis of participants' discrimination sensitivity and response bias indicate that people engaged in joint action make equally effective use of available agency cues under high and low coordination demands but tend to ascribe control of external events to the interacting group instead of an external source. The results are however inconclusive with respect to the source of this bias that could be likely explained through higher-order cognitive expectations, misdetection of sensorimotor discrepancies during external control trials, the congruency of observed and intended unfolding of perceptual events during external control trials or a combination of them. Thus, based on the results discussed so far, what cues people used to sense joint agency in the present study remains uncertain.

Confidence ratings

Interestingly, analysis of participants response confidence ratings showed that participants were more confident with reports of joint control compared to reports of external control under high coordination demands but not when coordination demands were low. Thus, although participants were biased to report joint instead of external control under high coordination demands, they were also more confident in doing so compared to reports of external control. As a potential explanation for this effect, enhanced pro-social attitudes could be made accountable that have been shown to arise under high degrees of interpersonal coordination (see Michael et al., 2016 for references). In particular, high coordination demands in the alternating tapping conditions may have enhanced rapport among participants and elicited stronger commitment to the joint activity which induced a stronger tendency for group-serving interpretations and responses. This could explain why participants tended to be overly confident in answering "we did" when being asked to report who they felt had been in control of the tones heard during sequence reproduction under high coordination demands. One could argue that enhanced pro-social attitudes in trials with high coordination demands should have likely led to a stronger bias to report joint instead of external control in this condition compared to trials with low coordination demands. Although this was not found to be the case inference statistically, the bias parameter was at least descriptively larger under high compared to low coordination demands, pointing towards this direction. If this interpretation of the results holds to be true, it would shed further light on the questions whether the source of the bias to report joint control instead of external control is rather cognitive or perceptual in nature. Together with the finding of higher confidence in reports of joint control under high coordination demands, it seems plausible to assume that the bias reflects, at least partly, effects of a general cognitive bias to attribute external events to the interacting group that may be enhanced when pro-social attitudes are strong. Thus, it could be concluded that the sense of joint agency relies to a certain extent on cognitive cues and motivational factors that can overrule the influence of more direct sensorimotor and perceptual cues.

Tapping performance

Error rates

Analysis of participants' error rates sheds light on the difficulty of the different task conditions and on the relation between the sense of joint agency and participants' overall task performance. It was found that trials in which participants faced high coordination demands (alternating tapping) were more error-prone than trials in which participants faced low coordination demands (sequential tapping). Moreover, participants who started the sequence (i.e. leaders) made fewer errors than participants who joined in (i.e. followers). As error rates were calculated based on participants tapping performance, these findings indicate that participants performed worse (i.e. reproduced the timing of the model sequence less accurately) under high coordination demands compared to low coordination demands and when they had the role of followers compared to leaders. This clearly shows that the task was more difficult when participants faced high coordination demands and when they had the role of followers.

Interestingly, the worse performance under high coordination demands or when participants had the role of a follower was not reflected in participants' joint agency ratings that were equally strong across conditions as reported above. This seems to contrast with findings of previous studies that showed joint agency to be stronger when joint task performance turns out as more successful (Loehr, 2018). However, this contrasting finding can again be accounted for by the different task setup in the present study. Crucially, in the present study, successful joint task performance (i.e. accurately reproducing the timing of the model sequence) was not a reliable indicator for joint control of the tones heard during sequence reproduction because it confronted participants with uncertainty whether their tapping performance had been indeed very good or whether the tone sequence was simply controlled by the computer instead. Thus, given the low reliability of successful joint task performance as a positive cue to agency in the present task, its influence on the sense of joint agency may have been weakened. If this interpretation is correct, it sheds further light on the proposal by Loehr (2018) that a central principle of cue-integration accounts of self-agency, namely that agency cues get dynamically weighted according to their reliability in a given situation (Moore & Fletcher, 2012; Synofzik et al., 2013), also applies to the generation of a sense of joint agency.

Efficacy of perceptual and sensorimotor cues to agency

To shed more light on the potential influence of sensorimotor and perceptual cues on the sense of joint agency, participants tapping performance was analysed with respect to their responses who they felt had been in control of the tones heard during sequence reproduction. By comparing the markedness of sensorimotor cues (i.e. height and variability of asynchronies between taps and tones) and of perceptual cues to agency in the task (i.e. tempo difference between model and reproduction tone sequence and temporal variability of the reproduction tone sequence) between trials in which participants reported joint control with trials in which participants reported external control, conclusions on the effectiveness of these cues on participants responses can be drawn.

Looking at the perceptual cues to agency that were available in the current task, it was first found that the mean tempo difference between model and reproduction tone sequence and the temporal variability of the tones heard during sequence reproduction were greater under high coordination demands compared to low coordination demands. This finding mirrors the results of the error rate analysis just outlined by showing that participants faced higher task difficulties and showed worse tapping performance when coordination demands were high. Furthermore, it indicates that perceptual agency cues were more salient under high coordination demands than under low coordination demands. Secondly, response-locked analysis of perceptual cues showed that both the mean tempo difference between model and reproduction tone sequence and the temporal variability of the tones heard during sequence reproduction were more pronounced in trials in which participants reported joint control compared to trials in which participants reported external control. Moreover, this was found to be the case to the same extent under high and low coordination demands. This clearly demonstrates that participants made use of these perceptual cues to inform their responses under both high and low coordination demands alike. Accordingly, as it was hypothesized, this points out an important role of perceptual cues for the sense of joint agency and shows that people monitor the purely perceptual unfolding of events arising over the course of a joint activity to evaluate agency at the level of the group. However, based on the data at hand, the stated hypotheses that perceptual cues have a stronger impact in joint action contexts that elicit stronger feelings of joint agency can't be confirmed nor falsified because joint agency was found to be equally strong under high and low coordination demands. Nevertheless, a potential conclusion from these findings could be that the equally strong feelings of joint agency under high and low coordination demands rest on the comparable extend participants made use of perceptual cues to monitor agency in the two conditions. As argued above, monitoring one's co-actor's actions was beneficial for examining control mode during the task irrespective of high or low coordination demands which made it equally likely in both conditions that participants took the action contributions of their co-actors into account to monitor agency during the task. As monitoring contributions of co-actors was only possible based on the purely perceptual unfolding of the occurring tones during sequence reproduction, the sense of joint agency that arose within participants may have been based in particular on these cues. An interesting question for future research would then be to examine whether the monitoring of perceptual agency cues constitutes a necessary condition for a sense of joint agency to arise. Of further interest is the finding that although perceptual cues were more salient under high compared to low coordination demands, participants seemed to rely on them to an equal extent in both conditions to sense joint agency in the task. Thus, higher salience of perceptual cues under high coordination demands did not result in a stronger impact of these cues on participants responses which would be expected if the principles of cue integration accounts of self-agency (cf. Moore & Fletcher, 2012; Synofzik et al., 2013) apply also to the generation of a sense of joint agency. However, cue saliency may only have an impact on the weighting of agency cues if a particular cue is more salient with respect to other available cues to agency. Thus, higher saliency of perceptual cues under high coordination demands may only influence the weighting of cues to joint agency if the saliency of e.g. sensorimotor cues was equal between conditions. Clearly, further research is necessary to shed more light on the question if and how the sense of joint agency rests on the same principles of cue integration thought to underly the generation of self-agency.

Looking at the sensorimotor cues to agency that were available in the current task, a comparable pattern of results was found. First, both the mean and the standard deviation of the absolute asynchronies between taps and tones were larger under high compared to low coordination demands, showing again that task difficulty was higher and participants tapping performance worse under high compared to low coordination demands. Accordingly, as was the case for perceptual cues to agency, sensorimotor cues were also more salient under high compared to low coordination demands. This fact, i.e. higher salience of both perceptual and sensorimotor cues under high coordination demands, could explain why the expectable impact of general cue saliency on the weighting of different agency cues was not reflected in the current results. Secondly, response-locked analysis of sensorimotor cues showed that both the mean and the standard deviation of the absolute asynchronies between taps and tones were more pronounced in trials in which participants reported external control compared to trials in which participants reported joint control and this was found to be the case to the same extent under high and low coordination demands. This finding clearly indicates that irrespective of coordination demands, participants also made use of available sensorimotor cues to inform their responses. Accordingly, it must be concluded that sensorimotor cues play a likely important role as perceptual cues for the generation of a sense of joint agency, disconfirming the hypotheses that sensorimotor cues would have only a minor influence on the sense of joint agency compared to the influence of perceptual cues. Considering the nature of the current task as well as theoretical conceptions of the sense of joint agency and of the processes underlying successful execution of joint action, this finding is, however, not too surprising. With respect to the nature of the current task, it would have indeed been surprising if participants would have disregarded available sensorimotor cues to agency at all as they were highly reliable indicators for distinguishing between control modes in the task. Faced with uncertainty whether the unfolding tones heard during sequence reproduction are due to the interacting dyad or to an external source, it seems that participants just made use of all reliable information available which obviously includes cues stemming from privately detected sensorimotor discrepancies. Moreover, a claim could be made that private sensorimotor cues, although being only very limitedly suitable for monitoring agency at the level of the group as a whole, may still receive a relatively strong weighting in cooperative joint actions because they allow the establishment and maintenance of a reliable discrimination between self and other (van der Wel & Knoblich, 2013). Although contributions of self and other were quite easily distinguishable in the current task due to the temporal distance between self- and other-issued actions, participants may still have used private sensorimotor cues to foster this discrimination and to monitor self-agency independently from joint agency. This possibility would also be in line with Pacherie's (2012) notion of *shared agency* thought to characterize the sense of joint agency in most joint action contexts, in which joint agency is experienced along with an intact sense of self-agency. Accordingly, it could be concluded that participants experienced a sense of shared agency during the current task and monitored joint agency in parallel to self-agency. The strong reliance on private sensorimotor cues found in the current study could then be explained as reflecting processes of intact and persisting self-agency monitoring during cooperative joint action.

Summary

Taken together, the main findings of the current study can be summarized along the following points: 1) Participants experienced more shared as opposed to individual control over the tones heard during sequence reproduction irrespective of coordination demands and role assignment indicating that people experience a sense of joint agency in cooperative joint action as soon as own and other's action contributions are taken into account to monitor the current agentic state of the interacting group. 2) People engaged in cooperative joint action tend to attribute control over external sensory events to the interacting group instead of an external source which can at least partly be accounted by a general cognitive bias to feel in control of events when interacting with others that may be further subject to modulations by pro-social attitudes or other motivational factors. 3) People engaged in joint action seem to flexibly combine agency related informative signals to monitor control of the interacting group over external sensory events including both private sensorimotor as well as publicly accessible perceptual cues. Moreover, there was some evidence that these performance-related cues can be partly overridden post-hoc by higher-order cognitive thought or other interpretative processes that may be furthermore subject to motivational factors. In the remainder of this chapter general implications of these findings for theories of joint agency are discussed followed by proposals for future avenues of research on the sense of agency in joint action.

4.2. Implications for theories of joint agency

What are the wider implications of the current study for theories of joint agency? The study set out to shed more light on the cues and mechanisms that underly the generation of this special agentive experience proposed to arise during cooperative joint action. First, the current study provides further empirical evidence for the proposal that people engaged in cooperative joint action do indeed experience joint rather than mere individual agency. Thus, the current study is in line with and confirms previous philosophical proposals (Dokic, 2010; Pacherie, 2012, 2014; Seemann, 2009) and empirical studies (Bolt et al., 2016; Dewey et al., 2014; Obhi & Hall, 2011) suggesting that agency monitoring in joint action extends to the level of the interacting group as a whole.

In terms of the necessary structural conditions for the generation of joint agency, the current study implies that the generation of joint agency seems to be independent from the degree of coordination between co-actors as well as their assigned roles within the joint activity. Instead, the findings of the current study imply that a sense of joint agency is generated as soon as people take action contributions of other co-actors into account to monitor the current agentive state of the interacting group. Any structural task condition that drives people to monitor not just their own but also the action contributions of their co-actors with respect to agency are thus prone to elicit a sense of joint agency.

Coming to the cues people use to derive a sense of joint agency, the current study highlights an important role of informative signals that are tight to the purely perceptual unfolding of the action effects emerging within a joint activity, pointing out an important role of perceptual cues for the sense of joint agency. This finding is in line with conclusions by previous empirical studies that have pointed out a central importance of predictions of action effects on a purely perceptual level for the generation of a sense of joint agency (Bolt & Loehr, 2017; van der Wel, 2015; van der Wel et al., 2012). However, the current study design does not allow to draw clear cut conclusions on the question of whether the found impact of perceptual cues is actually predictive or rather postdictive in nature (cf. Moore & Haggard, 2008; Synofzik et al., 2013). Although the impact of perceptual cues on the sense of (joint) agency is mostly explained within predictive internal models accounts of SoA (Jeannerod, 2009; Pacherie, 2010, 2014), the reliance on perceptual cues to inform agency responses in the current study can likely be explained by postdictive or inferential processes that match the observed perceptual unfolding of the sensory events to proximal intentions or to expectations how the perceptual events should have unfolded when being controlled by either the dyad or the computer respectively. Nevertheless, the found importance of perceptual cues for the sense of joint agency may be best explained by the fact that they allow to monitor self- and other-generated action contributions alike and thus are suitable to monitor agency not only on an individual level but also on the level of the interacting group as a whole. Whether the extent to which people make use of perceptual cues to monitor agency in joint action contexts also determines the amount of joint agency experienced during a joint activity or whether the use of perceptual cues constitutes even a necessary condition for the generation of a sense of joint agency, however, cannot be answered by the current study and remains an interesting question for future research.

An important implication of the current study with respect to theories of joint agency is the finding that not only perceptual cues but also private sensorimotor cues receive a central role for the generation of the sense of joint agency. Against the expectation that private sensorimotor cues may be weighted weaker in joint action contexts in which people experience joint rather than mere individual agency, it was found that the impact of sensorimotor cues on the sense of joint agency was comparable to the impact of perceptual cues. This points out that, although being only limitedly suitable to monitor agency at the level of the interacting group as a whole, informative signals tight to the immediate execution of private motor acts are not disregarded when agency is monitored in joint action contexts. This suggests that the sense of joint agency, although reflecting an agentive experience tight to the interacting group as a whole, is nevertheless anchored in and not independent from the agentive monitoring of purely individual action contributions which was also found in another recent study by Le Bars et al. (2020). Two, not mutually exclusive, cases can be made to explain the persisting impact of private sensorimotor information on the sense of joint agency. First, it is likely that in order to derive a sense of joint agency, people take their immediate sense of self-agency as a point of departure to examine further how much control is currently entertained by the interacting group as a whole. As private sensorimotor cues are of prime importance to establish a sense of self-agency (e.g. Knoblich & Repp, 2009; Moore et al., 2009) the potential anchoring of the sense of joint agency within the sense of self-agency could explain the found importance of private sensorimotor cues for the sense of joint agency. Secondly, many accounts of joint action highlight a crucial importance of establishing and maintaining a reliable discrimination between self and other for successful joint task performance (e.g. Knoblich & Sebanz, 2008). Moreover, as was pointed out already, the problem of self-other discrimination in joint action contexts arises in particular with respect to agency as on a purely perceptual level of action specification, action contributions of self and others are functionally equivalent and inherently ambiguous with respect to who caused them (cf. Jeannerod, 1999). Thus, for agency monitoring in joint action contexts it would be vital if people monitor their own contributions to the joint activity distinctively from other- and jointly produced action effects. From that, the case could be made that the found reliance on private sensorimotor cues when monitoring agency in joint action contexts fulfils at least to some part the function of establishing and maintaining a veridical and reliable sense of self-agency that would ease discrimination between self and other. How exactly the sense of self-agency and the sense of joint agency are interlinked when people experience shared agency over the course of a joint activity is clearly an open challenge for theories of joint agency.

Finally, the current study also points out that performance-related perceptual and sensorimotor cues are probably not the only factors underlying the generation of the sense of joint agency. Instead, the study provides indirect evidence that the sense of joint agency is to some extend also subject to higher-order cognitive expectations and interpretative processes that can override the influence of more direct cues to joint agency. Moreover, the results also tentatively suggest that the influence of cognitive factors on the sense of joint agency can be further modulated by enhanced pro-social attitudes or other motivational factors. However, this potential influence of cognitive expectations and motivational factors on the sense of joint agency cannot be evaluated conclusively based on the current study and further research is arguably needed to back up the stated claims.

Taken together, it seems that no single performance-related cue nor any thought alone underlies the generation of the sense of joint agency. In line with Pacherie's (2012, 2014) integrative framework of joint agency, the results of the current study, therefore, suggest that in order to derive a sense of joint agency, people dynamically combine a multiplicity of cues that are informative with respect to the current agentive state of the interacting group. These cues are bound to the monitoring of self-, other- and jointly produced action effects at different levels of action specification and control (sensorimotor, perceptual, and cognitive). However, the principles and mechanisms that underly the integration and weighting of these multiple cues remain underspecified and a matter of future debates. Whether principles of optimal cue integration that are assumed to underly the generation of self-agency also apply to the generation of joint agency has still to be examined. In this regard, the current study turned out as being unable to provide evidence for a specific weighting of agency cues as a function of the analysed joint action contexts or of the degree to which people experience a sense of joint agency.

4.3. Limitations and avenues for future research

The current study turned out as being unable to answer the stated research question that asked whether different joint action contexts that alter the strength of joint agency are marked by a specific weighting of available cues to joint agency. Future studies could follow up on this question by investigating other joint action contexts that are indeed able to elicit different degrees of joint agency within participants. The general study design and task procedure applied in the current study proved to be vital to examine the efficacy of sensorimotor and perceptual cues on the generation of the sense of joint agency and could be further adapted to examine whether different task conditions may change the weighting of these cues. One option would be to introduce highly asymmetrical roles between participants in the task (e.g. one participant being responsible for more then the half of the taps) which has been suggested to prevent strong feelings of joint agency (Pacherie, 2014) and compare it to a condition in which task demands stay symmetrical for both participants. Another possibility would be to compare one of the tapping conditions applied in the current study with a condition in which both partners issue their taps in synchrony with each other. Highly synchronized actions between participants would make it harder for them to differentiate the respective contributions of themselves and their partner and may shift their agentive experience towards a sense of we-agency (Pacherie, 2014) which may alter the weighting of sensorimotor and perceptual cues to joint agency. Another option would be to compare a joint action condition with a solo action condition of the task in order to examine whether jointly acting with others alters the weighting of certain agency cues compared to solely individual action contexts.

Future studies should also shed more light on the specific relationship between self-agency and joint agency. The results of the current study indicate that although people experience a sense of shared control over the unfolding actions within joint action contexts the experience of joint agency seems nevertheless to be anchored within a sustained sense of self-agency. With that, questions arise to which extend the sense of joint agency is determined by people’s experience of self-agency over their individual contributions to the joint task and how the sustained sense of self-agency is affected by a concurrently arising sense of joint agency. These questions are also connected to the question whether effects of joint action contexts on peoples experience of agency are best interpreted as reflecting a shift towards we-agency, i.e. a successive dissolution of self-agency within the collective agency of the interacting group, or as an extension and enhancement of self-agency (Pacherie, 2014). The results of the current study point towards the latter but more studies on the sense of agency in joint action contexts are needed to derive coherent conclusions on this issue.

Another avenue for future research is to shed more light on the role of motivational factors in the generation of a sense of joint agency. One suggestive interpretation of the current study results put forward that the effect of cognitive expectations and interpretative processes on the sense of joint agency may weight stronger in cases of enhanced pro-social motivations. Future studies could follow up on this proposal and examine it experimentally. One option would be to manipulate pro-social motivations by inducing and highlighting ingroup-outgroup relations among participants in the applied paradigm and examine whether this affects the found bias of participants to report joint instead of external control over external sensory events when interacting with each other. Closely connected are questions concerning the role of the affective valence of joint action outcomes. Do people engaged in joint action experience a stronger sense of joint agency for joint outcomes that have a positive affective valence and what potential role do interpretative processes play in these cases? For the case of individual actions, it has been shown for example that priming of outcome information in advance of action execution can increase the experience of agency as long as the outcomes are attached with positive affective value for participants (Aarts et al., 2009). It is likely that affective biases like this one are also at play in joint action contexts when people experience a sense of joint agency but systematic attempts to evaluate this claim are still missing. Future studies could for example examine whether people engaged in joint action experience a strong sense of joint agency for affectively positive outcomes even if their own contributions to the outcome were relatively unimportant.

Another important line of future research on joint agency is to establish experimental tasks that implement implicit measures of people's agentive experience when interacting with others. Although some studies found implicit measure such as intentional binding or sensory attenuation to be affected by social interactive contexts (Obhi & Hall, 2011; Strother et al., 2010; Weiss et al., 2011) it is still to be examined whether these measures are able to tap into feelings of joint agency or if they merely measure altered feelings of self-agency during social interactions. A potential approach would be, for example, to examine whether intentional binding can be found for jointly produced action effects that cannot be reduced to purely individual action contributions of either co-actor such as the harmonic sound of a piano chord played together by two individuals.

5. Conclusion

Understanding the cognitive foundations of the pervasive and profound feeling of being in control of what we are doing and of how the things in the world around us change accordingly – the sense of agency - constitutes a central challenge for the scientific inquiry of human behaviour and experience. Moreover, as humans entertain highly social lives that are marked by numerous and frequent instances of social interactions, investigations of when, how and at what scale the sense of agency arises, must take action contexts into account in which people act not in isolation but together with others to bring about changes in their environment. With this ambition in mind, the present thesis set out to explore how people derive a sense of agency in joint action contexts by focussing on the question of what informative signals people make use of to examine the current agentive state of their interacting group.

In line with philosophical accounts of the phenomenology of joint action and recent empirical studies in this domain, the present study yielded further evidence in favour of the claim that the sense of agency in joint action contexts reflects a sense of joint agency, meaning that action control and agency monitoring is centred at the level of the group and extends beyond purely individual action contributions. Against expectations, however, the sense of joint agency was not found to be modulated by the height of coordination demands people faced during the joint activity nor by their assigned roles as leaders or followers. Thus, the present study implies further that mutual coordination between co-agents and adaptation to other's action do not mark necessary conditions for the generation of a sense of joint agency. Accordingly, it can be concluded that strong feelings of joint agency can emerge within a wider range of structural joint action conditions than previously assumed as long as people are prone to take the contributions of co-actors into account when evaluating the agentive origin of external sensory events.

With respect to the informative signals people make use of to evaluate joint agency, it was found that people strongly rely on the monitoring of the purely perceptual unfolding of external sensory events, highlighting a central importance of perceptual cues for the generation of the sense of joint agency. Crucially and against the hypothesis that informative signals tight to the immediate execution of individual motor acts will be less important for the generation of joint agency, the present study provides evidence that private sensorimotor cues are likewise taken into account to monitor agency in joint action contexts, pointing out the importance of these cues for the sense of joint agency. This finding indicates that although people evaluate agency in joint action contexts at the level of the group, their agentive experience is deeply anchored within their immediate experience of self-agency. How these two levels of agentive experiences are interlinked remains, however, a topic for future research. Moreover, the present study also points towards a potential influence of cognitive expectations and interpretative processes on the generation of the sense of joint agency that are likely to be affected by pro-social motivations and affective factors. However, these interpretations of the results are only speculative and must be treated with caution until future studies examine them further.

Taken together, the results of the present study can be best accounted for by adopting an integrative framework of joint agency that is committed to the idea that the sense of joint agency arises through the integration and weighting of multiple cues stemming from the monitoring of self-, other and jointly produced action effects at different levels of action specification (sensorimotor, perceptual and cognitive). However, in order to provide a useful scientific framework that can trigger falsifiable research questions, cue integration accounts for the sense of joint agency must be further specified and explicitly probed by empirical studies. The current study provided a first attempt in this direction by investigating whether the weighting of cues to joint agency can shift as a function of the amount of joint agency experienced by co-actors or due to different joint action contexts. Unfortunately, the present study was unable to evaluate this question conclusively and further research is needed to test the stated assumptions.

Thus, research on the sense of agency in joint action remains a field with many open questions and tricky theoretical and empirical challenges. However, the relevance of the topic, the increasing interest in it among cognitive scientists and philosophers alike and the steadily growing body of empirical and theoretical work addressing it, raise high hopes that we are on a good way to approach a position from which we can finally answer how it really feels to act together and in what processes these feelings are grounded.

6. References

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