Observations on action-observation research: An autobiographical retrospective across the past two decades

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Abstract

When we watch other people perform actions, this involves many interacting processes comprising cognitive, motor and visual system interactions. These processes change based on the context of our observations, particularly if the actions are novel and our intention is to learn those actions so we can later reproduce them, or respond to them in an effective way. Over the past 20 years or so I have been involved in research directed to understanding how we learn from watching others, what information guides this learning and how our learning experiences, whether observational or physical, impact our subsequent observations of others, particularly when we are engaged in action prediction. In this review I take a historical look at action observation research, particularly in reference to motor skill learning, and situate my research, and those of collaborators and students, among the common theoretical and methodological frameworks of the time.

Preamble

I started studying action-observation processes before it was fashionable and before ideas about the so termed Mirror Neuron System (MNS) (for reviews Cattaneo & Rizzolatti, 2009; Rizzolatti & Craighero, 2004; Rizzolatti, Fogassi & Gallese, 2001) had pervaded thinking about how observation works (and apparently how easily it works!). My first foray was in 1997 when I was a PhD student with Ian Franks at UBC. I had been heavily influenced by Timothy Lee's research program at McMaster University in Canada and his attempts to probe motor learning processes through the study of bimanual coordination. I had worked as a Research Assistant for Dr Lee in the mid-90s (after finishing up my Masters' thesis with Dr Janet Starkes where I had been studying expertise in sport and the role of practice behaviours in defining elite performance). Dr Lee had been using a bimanual coordination apparatus to determine instructional influences on learning against the backdrop of known "habits" (the infamous in-phase and anti-phase, Kelso, 1984; see Fontaine, Lee & Swinnen, 1997; Swinnen, Lee, Verschueren, Serrien & Bogaerds, 1997; Tsutsui, Lee & Hodges, 1998; Wishart, Lee, Murdoch & Hodges, 2000). What had interested me was how understanding develops from watching, especially when we are watching actions that we cannot perform. So, not merely scaling tasks (doing something more accurately, or what Schmidt, 1975, would call "parameterizing"), nor sequencing together known actions, but actually performing novel complex skills, whose spatial-temporal relationships are distinct from those performed in the past. Related to this idea of understanding (in terms of relating/translating information in a way that can transfer to motor output), was how what we can do, or cannot do, influences what we can see. If we are unable to discern what to do from watching, because the actions are unusual and potentially complex, what information do we use to guide subsequent action attempts and are there downsides to using demonstrations to convey early understanding?

A brief overview of the format and chronological history

In making decisions about how to structure this review I have decided to provide a chronological description of some of my research that has been directed to these questions above, which I address within the context of popular conceptual frameworks at the time. My initial work during my PhD (as well as subsequently with my PhD student, Dana Maslovat, who I co-supervised with Ian Franks) was shaped, quite loosely, by dynamical systems ideas and the bimanual coordination paradigm. In particular, I was interested in the question, how do novel movements "emerge" against the backdrop of existing, yet undesirable movement preferences or habits? Because I was interested in how demonstrations impacted this process, some of this research was driven by the social-learning theory of Albert Bandura, particularly the role of mediating cognitive representations derived from watching others (e.g., Bandura, 1971, 1977, 1989; Carroll & Bandura, 1982, 1990). I was unable to let go of the notion of representations in my thinking about observational learning and sign up to the "dynamics" camp, so I did have some "fun" with reviewers!

In the 1980s and 1990s especially, observational learning research was heavily influenced by Bandura's thinking and cognitive representational ideas. Significant attempts were made to study how characteristics of the model impacted what is learned and whether cognitive processes engaged during observational practice (such as error detection) matched those engaged during physical practice. Much of this research was influenced by people such as Penny McCullagh, Luc Proteau, Maureen Weiss and David Wright (e.g., Black & Wright, 2000; Blandin, Lhuisset & Proteau, 1999; Deakin & Proteau, 2000; McCullagh & Meyer, 1997; Weiss, Ebbeck & Rose, 1992). Somewhat concomitant with the surging interest in dynamical/complex systems and ideas concerning constraints (Newell, 1985) and affordances (E.J. Gibson, 2000; Lee, 1998), was the "visual perception perspective" (VPP), proposed by Scully and Newell (1985), as a new approach to thinking about observational learning. Rather than the emphasis being on the primarily cognitive processes underpinning "how" we learn from watching others, the emphasis shifted to "what" information is used to aid observational learning. The shift was on the information itself and how spatial-temporal relationships between action components (i.e., relative motion) potentially constrain our attempts to copy what we see. This research and the testing of ideas related to the VPP, as well as some alternative accounts of key (goal-related) information shaping observational enactment (e.g., Bekkering, Wohlschlager & Gattis, 2000), had a significant impact on work I conducted during my post-doctorate and subsequent lectureship position at Liverpool John Moores University in the UK, with Mark Williams and students; including Gavin Breslin, Daniel Eaves, Paul Ford, Spencer Hayes and Rob Horn (all of whom have faculty positions in the UK and USA, with Spencer and Daniel continuing to conduct research related to action-observation processes).

Around the time I returned to Canada, ideas concerning the "mirror neuron system" (see Rizzolatti & Craighero, 2004, for a review) and strong links between action and perception had begun to gain traction, because now there was a neurophysiological basis linking observation to action. What this encouraged were ideas related to motor-system activation during observation (so termed motor simulation or motor resonance; e.g., Gallese, Keysers & Rizzolatti, 2004; Gazzola & Keysers, 2009; Jeannerod, 1994) and hence direct links (direct-matching) between seeing and doing (e.g., Rumiati et al., 2005). In this way, learning was seen as a somewhat implicit, resonance, process. Vogt and Thomaschke (2007) referred to motor involvement during action observation as early (as compared to late) mediation, based on this direct activation of the motor system when viewing demonstrations. In contrast, late mediation referred to activation of the motor system at the enactment stage, whereby physical action was needed to activate more cognitive-based representations acquired during watching, through some translation and calibration to the observer's motor system. This is not to be confused with ideas concerning cognitive-mediation (*cf.*, Bandura), where here, mediation refers to intervening cognitive representations that are formed during practice which aid subsequent translation into action.

In much of my work since this time I have been testing ideas concerning these simulation-related processes and whether observational learning should be best defined as a direct, motor-based (implicit) process, as well as how action experiences shape what we see and learn from watching others. This work has been primarily behaviourally based, although Dr Maslovat and I did attempt some fRMI /observation and bimanual coordination work which proved too costly to continue (see Maslovat, 2010). I have also just been involved with an EEG (electroencephalography) observational practice study with Dr Naznin Virji-Babul and her MSc student, Najah Alhajri, which we are in the process of writing-up. Here, asymmetries were shown between mu rhythm suppression as a function of physical and observational practice in a later observation phase. A significant portion of my work has been focused on the study of observational learning processes in a sensorimotor adaptation paradigm, whereby people learn to move in novel, visually rotated environments. This work has been conducted mostly with Nicole Ong and Beverley Larssen, but a number of other students have been involved in this work (primarily Tanis Burnett, Daniel Ho, Shannon Lim, Anthony Sze). The ability to study how observation affects subsequent re-enactment, particularly unintentional after-effects, provides a window into what is acquired during observation and how implicit processes related to motor planning get (or do not get) updated through watching others. This research has been influenced by conceptual ideas concerning internal models, particularly feedforward predictive control and the match between expectations of action and actual sensory consequences (whether these are one's own or another person's, e.g., Miall & Wolpert, 1996; Wolpert, 1997; Wolpert, Ghahramani & Jordan, 1995; Wolpert, Ghahramani & Flanagan, 2001).

We have asked similar questions to those above about potential resonance processes when people are watching action of others in order to make predictions about action outcomes, or watching others in order to learn how to make predictions about action outcomes. This line of research has been prompted by some of the sport-expertise literature and studies showing the importance of perceptual-cognitive processes in distinguishing high level skill (for a review see Mann, Williams, Ward & Janelle, 2007). Myself and students (particularly Desmond Mulligan, who started this line of research for his PhD, along with Keith Lohse, who was doing a post doctorate with us, as well as more recently undergraduate students; Ethan Chan, Meghan Zhu, Brynn Alexander and Mareike Kuhne, the last an exchange student from Karen Zentgraf's lab in Muenster, Germany) have been interested in questions concerning the conditions which might bring about motor-based predictions and the potential automaticity of these simulation processes based on the type of stimuli and type of training. In the remainder of this review I go into more detail about these various lines of investigation that have prompted my interest in the broad area of action observation and learning since my PhD work, 20 years ago.

The Research

<u>Bimanual coordination and observational practice</u>

In the early 1990s, one of the significant influences on the field of motor behaviour was dynamical systems theory and work by people such as Michael Turvey and Scott Kelso (e.g., Kelso, 1997; Kugler, Kelso & Turvey, 1982). In reference to learning, there were a couple of papers that were particularly influential by Zanone and Kelso (1992, 1997). Stephan Swinnen at the University of Leuven was also using this paradigm to study feedback-related effects on motor learning (e.g., Swinnen, Dounskaia, Walter & Serrien, 1997; Swinnen et al., 1997) and along with Nicole Wenderoth, he has continued to do influential work on the study of coordination processes for control and learning (for reviews see Swinnen, 2002; Swinner & Wenderoth, 2004). In these original studies, Zanone and Kelso showed how existing (intrinsic) movements (i.e., symmetrical and asymmetrical in and anti-phase movements), influenced the learning of new coordination movements. In addition to their interfering influence (described as attractor states), evidence was shown supporting the destabilization of anti-phase movements with practice of novel movements, such as 90° out-of-phase, where one limb leads the other by one quarter of a cycle (requiring the limbs to be moving in different directions at select points in the movement and not reversing at the same time). These movements were typically studied using a bimanual coordination apparatus as shown in **Figure 1** (yet applications related to in- and anti-phase coupling have also been applied to whole body coordination in sports and exercise; e.g., Eaves, Hodges & Williams, 2008; McGarry, Khan & Franks, 1999; Passos et al., 2008). One of the particularly appealing procedures associated with this task, that was attractive as a motor learning researcher, was the ability to probe existing preferences or movement habits, through what was known as a scanning task methodology, both before and after practice. Therefore, it was possible to assess not only changes to a practised task, but also changes to (or attraction) to other movement patterns.

Initially, my interest was mostly in instructional influences on the learning and destabilization of these movement patterns, not least because breaking away from an intrinsic, stable movement pattern was probably best achieved by avoiding that movement, rather than trying to reshape it (see Hodges & Lee, 1999; Hodges & Franks, 2000, 2001, 2002a,b). In addition to verbal and written instructions, however, I also studied the interplay between demonstrations and feedback and how observational learning (that is demonstrations interspersed with physical practice) affected learning of these novel coordination movements in comparison to pure observational practice (no physical practice during acquisition, just observation) (for distinctions between observational learning and practice see Vogt & Tomascheke, 2007; Maslovat, Hayes, Horn & Hodges, 2010). In one of the first studies where we studied how demonstrations impacted motor learning of a 90° relative phase pattern, there were no benefits associated with watching demonstrations of a to-be-acquired movement, in comparison to just letting individuals practice with task-relevant feedback. Not only did demonstrations fail to aid skill acquisition and retention, we also showed detrimental effects associated with watching correct, video demonstrations (Hodges & Franks, 2000). Although these effects were influenced by individual differences in performance assessed on an initial tracking pre-test (referred to as the scanning task), it appeared that the demonstrations served to highlight (and attract) individuals to a pre-existing movement pattern, at the expense of trying new movements and bringing variability into practice in order to help "break-away" from these more stable movements. Therefore, prescriptive methods of instructing, which were based on the assumption that telling or showing someone what to do will lead to facilitated learning, actually failed to aid acquisition and in some cases hindered learning. We argued that without understanding of what was required, which is a function of actual motor experience, individuals were only able to pick up strategies. In the case of these novel bimanual movements, the strategy was likely "not to do in-phase", which was not helpful in that it discouraged exploration, shown by a persistence to anti-phase movements and an avoidance of in-phase.

In the case of these novel movement patterns, we argued that an effective cognitive representation or perceptual blueprint (an effective image of what to do), was not obtained merely through watching. The understanding of what was observed came about through doing. In follow up work, we showed that this understanding of what to do and interpret the demonstration was enhanced by video-feedback that matched the demonstration (Hodges, Chua & Franks, 2003). We argued that video feedback enhanced the discrimination of what was "desired", as also shown by better perceptual discrimination of tests of ability given after physical practice. Different to interpretations of the role of feedback in observational learning, described by Caroll and Bandura (1982, 1990), we argued that video feedback provided comparative information to help interpret the desired movement goal and hence form the perceptual blueprint/cognitive representation. Therefore, the role of feedback was not merely as a tool to evaluate performance in reference to what was desired but actually to help determine what was desired. In later work with Dana Maslovat, we were able to show that observational practice of a learning model (in the absence of physical practice) was able to facilitate perceptual discrimination processes, but that learning as assessed through behavioural measures, was not significantly improved in comparison to no-practice control conditions (Maslovat, Hodges, Krigolson & Handy, 2010). Although others have shown benefits from repeated observations of similar types of movements (e.g., Buchanen, Ryu, Zihlman & Wright, 2008; Buchanen & Dean, 2014; Buchanen & Park, 2017), which may in part be related to the type of tasks (single limb vs. dual limb), the type of feedback and length of the retention session, what these studies show is that discerning what to do from action observation is not merely an automatic matching process.

Rather, it is based on action capabilities and awareness of what not to do (self-feedback), and hence relationships between co-evolving action and perception processes (see also Wilson & Bingham, 2008; Wilson, Collins & Bingham, 2005 for similar ideas). These early observations have since been verified through work prompted by studies of the human MNS and observations of a tight coupling between action experiences and perceptual based processes (e.g., Calvo-Merino et al., 2005, 2006). I return to these ideas in the final section.

One final point to make with regards to the development of cognitive representations and how this is aided by demonstrations and dependent on the task, is the idea that the formation of an effective cognitive representation is meant to facilitate perceptions of self-efficacy (e.g., Bandura, 1977; Feltz, Landers & Raeder, 1979; Rosenthal & Bandura, 1978). Although personal success is the best way of enhancing perceptions of efficacy, vicarious experiences watching others succeed can also lead to heightened perceptions of ability in oneself. In a recent study we conducted, where learners watched a 2-ball juggling motion, we showed that observational practice, in the absence of physical practice, led to a steady increase in perceptions of ability and helped to restore confidence in ability when failures were later experienced through physical attempts (Hodges & Coppola, 2015). Although perceptions of ability and actual performance were somewhat congruent, the match was not as good as one might expect, suggesting a disconnect between what we see and think we understand and what we can do. I think this research also has a cautionary note when blindly using demonstrations to aid learning. Whilst observations might make people feel more efficacious, this can have significant consequences when individuals wish to attempt novel actions that are not well mastered or perhaps may be unsafe. We speculated that there may be individual differences in efficacy perceptions following observation, in that some individuals who were not very good at juggling, appropriately failed to raise their perceptions of ability when watching successful performances, whereas others, continued to have high expectations despite physical practice experiences to the contrary. This may be related to the popular Dunning-Kruger effect (e.g., Kruger & Dunning, 1999), whereby people who lack competency in a skill or knowledge show unawareness of this incompetency (at least as compared to others). The knowledge required to know what to do is the same knowledge which gives a person insight into what they do not know. The question as to how demonstrations shape ability perceptions (and the subsequent match between these knowledge systems), is something I hope to continue to explore.

Visual perception perspective

Alongside the shift in thinking that was happening in motor control, with regards to actions as consequences (or emergent features) of conditions in the environment and dynamical systems theory, there was also a shift in thinking about action observation. The direct perception approach (first espoused by J.J. Gibson, 1979/1986 and later reconsidered by David Lee among others; e.g., Lee, Lishman & Thomson, 1982), had led researchers to (re)consider what information affords action, rather than the question of how information produces action and the associated (cognitive) mediating processes. Karl Newell, along with his student at the time, Deidre Scully (Scully & Newell, 1985), took that approach to asking questions about key information underpinning action observation and particularly, observational learning. They proposed that relative motion information which defined the spatial-temporal relationships between limbs (e.g., legs and arms) and joints (e.g., shoulder, elbow and wrist), was directly perceived and as a consequence, constrained action reproduction in an observational learning context (for examples of angle-angle plots, which were a common means to show relative motion data, **see Figure 2a**). It was thought that observers were most attuned to this information and as such, it was thought to be the constraining information needed for successful perception and as a consequence, action reproduction.

These ideas led to research using what were termed, Point-Light-Display models (PLDs), as a way of conveying relative motion information in a salient way (as opposed to typical video format). An example of a point-light model is shown in **Figure 2b**, taken from stimuli used in a study outlined below (Hayes, Hodges, Scott, Horn & Williams, 2007). Motion analysis systems are typically used to capture actions (through reflective markers or LEDs) and then the actions are played back in this PLD format to observers. There had been evidence in psychophysical-related research showing that point-light models conveyed significant information about action and object properties, such as the weight of a lifted box (e.g., Cutting & Profitt, 1982; Johansson, 1973; Runeson & Frykolm, 1983). Because PLDs specify key relative motion information about the action, it was therefore argued that this was the information that individuals were attuned to in order to both act and make judgements about others' actions. In sports, there was some evidence that point-light models were potentially a useful device to convey relative motion and encourage observational learning. For the learning of dance actions, evidence was presented showing this type of model was more effective than video models (Scully & Carnegie, 1998). Questions concerning the effectiveness of this method and how information constrained action (through manipulations to PLD models, feedback, requirements to imitate or attain an action goal), became the focus of my research during my time at Liverpool John Moores University.

Despite the initial enthusiasm concerning the potential of PLD models to aid observational learning, positive effects were not replicated in comparisons of video and PLD models in an underarm dart-throwing task (Al-Abood, Davids, Bennett, Ashford & Marin 2001), nor in some of our own work studying the reproduction of a soccer kicking action, either with or without outcome or visual feedback (e.g., Horn, Williams, Scott & Hodges, 2005). During my post-doc, Mark Williams and I had the pleasure of “inheriting” one of Dr Scully’s students, from Queen’s University in Belfast, as she was retiring from academia. Gavin Breslin was interested in furthering his understanding of modeling effectiveness and was keen to evaluate some of the ideas based on the point-light method. This ended up forming his PhD work, where he travelled between Liverpool and N. Ireland to consult and collect data using a cricket bowling action. This action was chosen due to its relative novelty and the coordination required between the arms, between joints of the bowling arm, as well as on a whole-body level. We were also able to measure outcome success in addition to modeling of movement form. In none of our studies (using this action, or others), did we show benefits associated with PLD versus video models, even though both facilitated observational learning in comparison to not watching or just physical practice (Breslin, Hodges, Williams, Curran & Kremer, 2005, 2006). Indeed, in work with Spencer Hayes, when we compared these types of models with 7 yr old children watching lawn-bowling actions, not only did PLDs not help learning, but they led to worse acquisition and retention than video models (Hayes, Hodges, Scott et al., 2007; see also Figure 2). One of the funny observations here, was that we would show a PLD video to the children and some would just reproduce a completely different action to that which was shown. This made us abandon our refined 3D measurement system to capture specific coordination patterns, and instead revert to video to classify aspects of the action which were replicated. For example, one child just walked with one arm straight out in-front of him, like a robot, and some kids just reported seeing stars! Having a ball to physically bowl on reproduction attempts, did at least lead to bowling actions, when watching PLDs. Somewhat counter to this, however, both children and adults were worse in replicating the form of the actions when they were tasked with actually achieving an action outcome (i.e., bowling), rather than only replicating movement form, particularly when watching videos. This raises interesting questions about methods we adopt when teaching through demonstrations and potential benefits or costs of requiring replication of action effects. Making the action goal salient, puts the emphasis on the action goal, at the expense of the desired kinematics (when this is important), what Gentile referred to as "goal confusion" (Gentile, 1972). Yet, requiring reproduction of an action goal, with the task-relevant constraints, allows the learner to figure out what to do without much guidance needed from demonstrations/instructions (for discussion of these issues see Hodges & Franks, 2002b, 2004a,b, 2008).

We asked the question as to whether relative motion was the constraining information on action-reproduction, or whether individuals were potentially attuned to other, salient information sources that more simply convey what to do. In particular, we tested ideas concerning end-point information as key constraining information on action reproduction, where individuals are most concerned with actions related or close to the action-effects, and less concerned with more proximal information that is potentially more varied across trials. This was based on a number of ideas related to the working-point (Bernstein 1940s, translated and reformulated by Latash and Turvey; Bernstein, Latash & Turvey, 1996), which later led to the concept of the uncontrolled manifold and different types of controlled/task relevant and uncontrolled/task irrelevant variability; Latash, Scholz & Schöner, 2002). Through occlusion of the end-effector, evidence had been provided showing how critical this end-point information was for differentiating various motor actions (e.g., Mather, Radford & West, 1992; see also Mataric & Pomplun, 1998; Morasso, 1981). Harold Bekkering and others (e.g., Bekkering et al., 2000) had also described evidence showing that children and adults were particularly attuned to information related to what to do (i.e., action goals), at the expense of how to do it. Because of the primacy of action goals and end-point information, we argued that action reproduction should be viewed more as an emergent feature of these goal constraints, rather than a direct approximation of action as relayed by relative motion. What we copy is what gets us to the action goal and is distally related to that goal. Our global perceptions are shaped by relative motions of the whole action, but for the purpose of learning and re-enactment, watchers are strategic and selective in attunement to key information relating to end-point success. This may even be information related to how an action should be scaled (or parameterised), when relevant to the action goal (Hayes, Hodges, Horn, Scott, & Williams, 2006).

In a series of studies we manipulated the type of information available to observers, through selective editing of video and point-light models. We would remove information specifying relative motion information, such that individuals could only see one joint (e.g., the wrist in cricket bowling or the toe in producing a soccer-kicking action). In these cases, they were shown full size images (so they could calibrate the actions to their own space), and were aware of what was being shown (i.e., a marker on the toe or wrist). With this minimal constraining information, learners were able to reproduce quite complex actions, as effectively, or for some measures, more effectively, than what was afforded from seeing the whole action or at least being privy to relative motion information (e.g., Hodges, Hayes, Breslin & Williams, 2005). For the cricket bowling action, being able to see the relative motion between joints of the bowling arm facilitated acquisition, in comparison to only viewing the wrist, although in comparison to a no-observation control group, all models led to improvements in replication of absolute movement time to more closely match the fast actions of the bowler (Breslin et al., 2005). In a follow up study, again involving a cricket bowling action, comparisons were made across progressively more sources of information, rather than just the type (i.e., just the wrist, or both wrists, or all the joints from one arm; Breslin, Hodges, Williams, Kremer & Curran, 2006). Here, the *amount* of information within a display seemed to play a more important role in constraining movement reproduction than the *type* of information.

Between-limb coordination was well replicated in groups that saw a demonstration, even if they only saw one limb. We argued that what was approximated from viewing the model was indeed constrained by what was seen, but that the actions were a by-product of constraints on the other limbs. Again, acquisition of coordination was more of an emergent feature of observational learning, rather than a direct approximation of the model. Indeed, when we manipulated *when* sources of information were introduced into practice of this action, coupled with measures of visual search, we showed that irrespective of what information was shown (i.e., only the bowling arm, both arms, whole body), eye gaze was mostly directed to the model's bowling arm (i.e., the "end-effector"; Breslin, Hodges & Williams, 2009). This supported the idea that the end-effector was an important perceptual constraint early in observational learning. In other work involving a lawn-bowling action, when comparing groups that were allowed to physically imitate with an actual ball, as opposed to just imitate the action, only in the no-ball groups, was full-body, relative motion information useful in aiding reproduction of the desired movement (Hayes, Hodges, Huys & Williams, 2007).

In addition to evidence showing that end-effector information is prioritised in observational learning studies, we also showed benefits associated with showing only the trajectory of the end-point of the action (i.e., the ball flight), rather than the actual kicking action, in learning a soccer kicking action (Hodges, Hayes, Eaves, Horn & Williams, 2006). In this task, individuals watched and/or were required to scoop-kick a ball off the ground in order to get it over a barrier to land on a target. In a number of studies with both novice and skilled soccer players, we also presented information showing how important this end-point (in this case ball flight) was for movement planning and motor control in skilled athletes (e.g., Ford, Hodges, Huys & Williams, 2006, 2009; Ford, Hodges & Williams, 2007). In summary, this research helped to elucidate on what information is used when copying actions and how this information is highly dependent on the action, the learner, the instructions and demands of the task (for a review see Hodges, Williams, Hayes & Breslin, 2007). In many ways, this research underscored the growing significance of the constraints-based approach to skill acquisition and consideration of interacting, non-prescriptive factors in constraining and creating movement behaviours (Davids, Button & Bennett, 2008; Renshaw, Davids & Savelsbergh, 2010).

The action-observation network and motor simulation

I have been studying processes which bring about change in behaviour through observation and how, when we watch others, our own actions and skills help us understand, make predictions, copy and learn. In this final section I review research primarily from my time as a faculty member at UBC, where I have been interested in what watching involves when people are trying to predict action outcomes from others (1) and when intentionally trying to adapt and learn (2). This research is based on ideas related to common coding (of perception and action) and the theory of event-coding (Hommel, Müsseler, Aschersleban & Prinz, 2001; Koch, Keller & Prinz, 2004; Prinz, 1997) as well as the notion of action (and perception)-simulation, whereby actions and perceptions share a common 'representational' format, leading to motor system involvement during action observation (e.g., Blakemore & Decety, 2001; Rizzolatti, Fogassi & Gallese, 2006; Schütz-Bosbach & Prinz, 2007).

1: Action observation and prediction

Motor system activation during action observation has received significant attention over the past two decades due largely to evidence of a mirror neuron system (MNS) in humans, also more broadly known as an Action Observation Network (AON, Caspers, Zilles, Laird & Eickhoff, 2010; Cross, Kraemer, Hamilton, Kelley & Grafton, 2009). Evidence has been presented showing that action observation activates similar cortical areas involved in actual execution and as such, action observation is thought to involve different processes depending on action experience. Familiar actions are thought to activate sensorimotor areas of the cortex (premotor, parietal) before progressing top-down to visual regions, and are thought to be moderated by requirements to make predictions (Schubotz, 2007; Urgesi et al., 2010). There is, however, ambiguity surrounding the type of stimuli and perceptual cues that promote such motor-based perception. Unfamiliar actions, in contrast, are thought to be first processed visually before potentially progressing (bottom-up), to motor-related areas (e.g., Gardner, Goulden & Cross, 2015). These ideas are related to distinctions between dynamic simulation and static matching, with the latter describing processes engaged when just holding an image in memory (e.g., Springer, Parkinson & Prinz, 2013; Stadler et al., 2011). There have been disagreements about the definition of “familiar” and the types of experiences that engender motor-simulation (e.g., Schubotz, 2007), as well as how best to promote motor-simulation (for a review see Zentgraf, Munzert, Bischoff & Newman-Norlund, 2011).

Over the past 20-30 years, researchers have been studying differences in the perceptual-cognitive skills of expert and less expert athletes, in dynamic sport domains, such as rugby, soccer, tennis, cricket and hockey (for reviews see Broadbent, Causer, Williams & Ford, 2015; Hodges, Starkes & MacMahon, 2006; Mann et al., 2007; Memmert, 2009; Müller & Abernethy, 2012). Much of this research has shown that experts are not only better than non-experts at predicting action outcomes from watching videos (i.e., faster and also more accurate), but that they show these advantages relatively early in the unfolding of an action. As such, expert anticipatory judgments are typically based on early movement kinematics and much of the research (through visual occlusion paradigms and studies of visual gaze tracking), has been directed to understanding what perceptual cues are used to make predictions about various action events. Because of this focus on key kinematic cues, the emphasis has been on the visual-perceptual process and the idea that these skills are predominately acquired through visual experiences. Although it has been acknowledged that these visual experiences need to be tied to action experiences (e.g., fans who have acquired visual experiences do not show the same visual skills as sports players; e.g., Williams & Davids, 1995), the emphasis was still on the acquisition of perceptual experiences that underlie superior perceptual-cognitive skills in sport.

Influenced by research directed to motor simulation and the AON, one of the first studies to challenge this idea was conducted by Aglioti, Cesari, Romani and Urgesi (2008). Not only did they replicate past effects showing players were better at predicting outcomes of a basketball free-throw shot (in or out) than fans and coaches or novices, but they also provided some evidence that these predictions were mediated by motor-based simulation. This was shown through Transcranial Magnetic Stimulation (TMS), a small magnetic pulse applied to representations of the wrist/forearm muscles in the primary motor cortex and measurement of the Motor Evoked Potentials (MEPs – as inferred through electromyography) in these muscles. Very simply, MEPs were higher in athletes when they viewed basketball free-throws, although this was true for both fans and athletes. However, only the athletes showed moderation of MEPs in relation to whether the action was successful or not. This led the authors to suggest that action experiences and motor-simulation type processes underlie successful decision processes in athletes. Because of the lack of control over the visual and action experiences of the athletes and the lack of sensitivity of MEPs in actually distinguishing across the fans and athletes with respect to overall decision accuracy, it was not possible to conclude from this research whether these motor-based activations were directly related to accuracy in predictions, or were perhaps a by-product of experience. Although there is considerable research showing that predictive judgements by athletes in a range of sport, in response to watching actions in others, engage areas implicated in the MNS and broader AON (for recent reviews see Karlinsky, Zentgraf & Hodges, in review; Smith, 2016), it is still difficult to know how relevant these cortical activations are in arriving at correct decisions. These outstanding questions formed the basis of the studies I review below where we have used a behavioural, motor-interference paradigm to determine the motor-system's involvement in the accuracy of decisions. It is important to point out, however, that this research has only been conducted in a task that requires no (complementary) action response, such as would be required if you were anticipating the direction of a serve or run in an opponent so you can move to intercept. Although we are starting to look at these processes in a broader context (using a soccer task; see also cricket research by Sean Müller and students in Australia), as yet, these studies have been limited to the prediction of landing outcomes of a thrown dart.

In an initial study, we controlled the visual-action experiences of our sample by conducting a training study. Individuals learnt to throw darts, either through physical practice (aiming for the top, middle or bottom centre of a dart board), observational practice, or through physical practice without any visual feedback (i.e., vision was occluded when the dart was thrown and only outcome feedback pertaining to the landing position was provided, Mulligan & Hodges, 2014). There was also a no-practice control group. Before and after practice we tested the accuracy of the participant’s predictions as to landing outcomes of a trained model, when the video was edited to occlude at various points in the unfolding of the action (for an illustration of the procedures see **Figure 3a&b**). We were particularly interested in whether post-practice predictions would be improved as a result of physical (motor-only) practice in the absence of vision, given that these prediction tests were tests of perception ability (not action). Indeed, we showed that both physical practice groups, regardless of visual feedback, improved on post-test prediction accuracy, in comparison to both the control group and a pure, observational (visual) practice group. Surprisingly, there were no benefits from matched visual experiences of the observers, rather, motor experience seemed to be driving benefits on these ostensibly, perceptually-based, decision tests. The observers also failed to show significant improvements in their actual motor performance post-practice, in comparison to the control group.

This initial study led us to question how these predictions were being made by the physical practice groups and whether we could better isolate the processes through tasks designed to probe (interfere) with the motor-system during the actual prediction task. In our first study, we only manipulated what people did in practice, not what they did during the prediction task. Therefore, we adopted a simple, motor interference task, where individuals were required to push lightly against a force gauge with their throwing (right) arm (i.e., the same arm as that observed in the stimuli), as they watched the video and made their predictions. In order to test whether these predictions engaged the motor system, we first decided to test these methods with visual-motor “experts” on this task (Mulligan, Lohse & Hodges, 2016a). In comparison to participants that had no experience playing darts (i.e., novices), only the skilled darts players were negatively affected by the motor secondary task (and not by an attentional, tone monitoring control task). The data from this study are illustrated in **Figure 4**, where we have plotted the prediction accuracy of the novice and skilled darts players as a function of condition and occlusion frame during the prediction task. The prediction accuracy for the skilled players was better than the novices in all conditions, except under this “motor” (force) condition, where accuracy was matched to the novices. Interestingly, decrements in performance of the skilled participants were shown at the earliest occlusion points (frames 1 and 2 of the forward propulsion phase of the dart), suggesting that this simple force monitoring task had interfered with the ability of these skilled performers to infer outcomes from these early kinematic cues. Because the interference was only shown for the force task, and not for an attention-matched task that required monitoring of tones, we surmised that this effect was due to a motor-based interference associated with the prevention, or inhibition, of processes typically engaged to make these predictions, likely related to action-simulation. Moreover, these effects were present when predictions were made about the landing outcomes of darts thrown by our trained model (as shown in Figure 4), as well as when we showed edited videos of the participant (i.e., self-observation, not shown). Congruent with a motor simulation based account, when participants made predictions about their own throws, accuracy in predictions was greater (although the degree of interference across both stimuli was comparable).

In a subsequent study, these effects were replicated among individuals who received short-term physical practice (Mulligan, Lohse & Hodges, 2016b). This time, we also compared interference from performing both a right and a left-handed force monitoring task (still right-handed participants practising throwing with their right hand), and our main comparison group was a perceptual-training group. This latter group, rather than passively watching, as is typical in observational learning studies, practised making predictions on edited videos with feedback (what is known in the sport expertise literature as perceptual training). When we tested post-test predictions, only the physical practice group showed interference from the right-hand force task. The left-hand force task did not interfere with prediction accuracy. Moreover, although the perceptual training group improved in their prediction accuracy post-test, to a similar level as that seen for the physical practice group, they showed no interference from any of the secondary tasks. These results further supported the claim that these predictive decisions were based on simulative processes, but only for people who had physical/action experiences and hence relied on their motor system to make accurate predictions.

The effector-specificity effects for the right-force task suggested that potential simulation processes were either specific to the action experiences of the decision maker (i.e., right-handers, throwing with their right hand) and/or the match between the action-experiences of the observer and the hand used to throw by the model in the prediction task. We are currently running studies to test these specificity effects, comparing right and left-handed individuals watching right and left-handed clips (with the latter being a reversed video of the right-handed thrower to match content). Based on data collected so far, it appears that practice experiences only translate to improved prediction when there is a match to the hand used by the model. This suggests a high degree of specificity of motor training experiences to prediction processes and simulation-type mechanisms. We have yet to test the transfer from opposite hand perceptual training (i.e., we have only looked at physical practice experiences thus far). Based on current data, we expect to see improvements pre- to post-practice, and hence generalization following perceptual training. This research has potentially important implications for methods of training and determining efficacy of training dependent on the end goal (e.g., transfer).

One other line of research we are pursuing with this task is to test how enduring or automatic these prediction processes are in the face of changes to motor and perceptual experience. Based on data that we are currently preparing to submit and that has been presented at a conference, we have some intriguing evidence showing that if we follow-up physical practice with perceptual training, any force-task interference effects that initially show up disappear, even though accuracy is maintained (Mulligan & Hodges, 2016). This suggests that perhaps these simulation processes are not automatic and/or that they can be overridden by higher-order perceptual/strategic decisions. It has been suggested that these perceptual representations need to be acquired separately from the action experiences in order for the observer/predictor to be able to flexibly switch between prediction strategies. This idea is congruent with work conducted with goal-keepers in comparison to outfield soccer players, with the former showing less resistance to fakes that would result from an automatic, action simulation process (Tomeo, Cesari, Aglioti & Urgesi, 2013). Surprisingly, when we reversed the order of training, going from perceptual training to physical training, we again failed to see any interference from the secondary motor tasks (following either type of training). This suggests that these visually-acquired processes and representations trump those acquired from (visual)-motor experiences. We are also planning to test a group that watches videos of their own throwing action on the second day of practice, to test whether this self-observation still changes the nature of how predictive decisions are made by observers, with the prediction that watching oneself may continue to promote more motor-based simulations.

In summary, this line of research has given us insight into the types of training experiences and contextual factors that impact on how we make predictive decisions about our own and other's actions. Although our data is to date behavioural (we are hoping that through collaborations with Karen Zentgraf in Germany that we will also collect some fMRI data), there is strong evidence that the mechanisms underpinning prediction processes in these tasks are motor-based, but only when the individual has acquired knowledge about the task through physical practice. Perceptually-based mechanisms and strategies (i.e., when the hand ends here, the dart will go here), appear to dominate prediction processes when this source of information is available. Merely acquiring visual experience when throwing (i.e., typical visual-motor practice) is not sufficient to gain this information which might positively endorse perceptual-training methods. However, we would also caution about the use of these perceptual-training methods at the expense of physical practice. We know that what is acquired from seeing, is qualitatively different from what is acquired from doing (at least in terms of processes engaged during the prediction task), raising issues about what is being learned when actions are divorced from the perceptual experiences. In the final section below, I echo this sentiment based on research we have been conducting using an observational learning paradigm under conditions where novel mappings are learned between actions and their sensory consequences.

2: Learning to adapt from watching others

One paradigm that has grown in popularity over the past few decades is that of a special type of learning termed adaptation learning (for reviews see Shadmehr, Smith & Krakauer, 2010; Wolpert, Diedrichsen & Flanagan, 2011). In some ways, this is a special case of parameterising a motor skill, as in effect, a person learns to adapt a well-learned simple movement, such as reaching or grasping, to novel sensory or motor constraints. It might also be viewed as a change in attractor dynamics (depending on your theoretical perspective), given that a preferred movement needs to be destabilized to give way to a novel visual-motor behaviour. There are two typical laboratory based environments that are used to assess how people adapt: a dynamic/motor based adaptation, where people are aiming with a device, such as a robot arm, and during the movement a movement-dependent force is applied, or a visual-based adaptation, where the visual feedback about the movement is altered. The latter is called, visuo-motor adaptation, because a change in the visual environment, such as a 30° clockwise rotation, requires a change in the motor plan. Typically, this latter paradigm requires that people make fast movements to or through targets, so that it is the planning processes that are affected/updated and not necessarily (or just) the online control of movement.

Much of the research related to adaptation learning has been conceptually situated in an internal model framework (again see Shadmehr et al., 2010; Wolpert et al., 2011 for reviews). In this framework, internal models are like memories for actions and because of past experience, they allow some (feedforward) prediction of what a movement will look or feel like. This predictive process has been termed the forward model and in an adapted environment, where sensory consequences do not match predictions, it is this model that is thought to be implicitly updated. Here, proprioceptive feedback about what is “normal” needs now to be calibrated to a new visual environment, so that a new normal is developed with a different rule or mapping between visual and proprioceptive feedback. As a consequence of practice and feedback in an adapted environment, the plan for the movement is also updated (termed the inverse model), such that with practice, a movement is planned differently and the predicted sensory consequences associated with a movement also change to match the plan and outcome goal.

One of the hallmarks of this adapted process is the phenomenon of after-effects. When a person learns to move in a rotated environment, for example, once they stop moving and are now knowingly transferred back into a normal environment, they continue to show biases reflective of their previous learning. Instead of moving straight ahead to a target as instructed, they will typically aim to the left or right of the target. These after-effects usually start out quite large (approximately half the size of the original rotation) and dissipate quite rapidly over time.

However, the rate of decay is dependent on availability of feedback which would alert to differences and although there is decay, after-effects have also been shown to be quite persistent over time, despite attempts to wash-out (or remove) these effects (e.g., Krakauer & Shadmehr, 2006; Lim, Larssen & Hodges, 2014; Scheidt, Reinkensmeyer, Conditt, Rymer & Mussa-Ivaldi, 2000). These after-effects reflect the fact that the motor plan for the movement has been changed or updated and that because these effects are evidenced, even though a person knows that they should be performing "normal" movements, this suggests that there is no longer a perceived discrepancy between predicted and actual sensory consequences (i.e., what a movement should feel and look like).

When I first started using this paradigm with Nicole Ong, a Masters' student at the time who had become interested in this topic after taking a graduate class with a colleague at UBC, Romeo Chua, we were interested in the question as to whether adaptation can occur without physical movement experiences. Importantly, we wanted to know whether, after watching another person perform in an adapted environment, one's own motor system is updated, such that the observer too shows after-effects. A group of researchers at the University of Western had used a dynamic adaptation paradigm to show evidence that observers could learn from watching others, that is, they could perform more accurately than a control group when first transferred to the watched adapted environment (Mattar & Gribble, 2005). They had suggested that this observational learning process was similar to that of physical practice, involving motor-system updating and feedforward predictive processes. However, although they showed that a secondary motor task (but not a simple cognitive task) interfered with observational learning, they did not test for the presence of after-effects through unanticipated catch trials, to test whether any improvements were evidenced in terms of the implicit motor plan (hence true adaptation, Redding & Wallace, 1996, 2002). This is harder to do in a movement-dependent force-field task and hence we decided to evaluate what is learned from watching others move in a visuo-motor adaptation task.

In a first study, observers watched the feedback of a live learning model, seated to the side of the observer (Ong & Hodges, 2010). They were able to see a video of their yoked partner's arm and hand as well as the rotated feedback of the cursor moving 30° clockwise (CW) to the actual arm. Movements were made and recorded on a graphic's tablet that was housed in a blackened environment, where an upturned monitor projected 5 radially aligned targets and rotated cursor feedback onto a semi-silvered mirror (see **Figure 5**). Before and after practice, we assessed performance in a known, normal environment without any cursor feedback (just targets). After practice, only the physical practice participants showed evidence of after-effects, regardless of whether they did or did not see the normal movements of their hand concurrently with the cursor feedback, although after-effects were larger when they could see their own hand. When transferred to the adapted environment, the observers showed significant savings from watching their partner, showing evidence for direct learning benefits. This latter finding supported that of Mattar and Gribble, showing that people learn from watching others move in these perturbed environments (what are referred to as direct effects of observation). However, the absence of after-effects in observers suggested that the learning was qualitatively different from that evidenced by physical practice participants.

For observers, there was no evidence that the motor-system was (implicitly) updated as a result of observation. Rather, based on analysis of strategy probes and explicit knowledge demonstrated after practice, learning appeared to be primarily a strategically driven process, where individuals had learned, from observing, that a certain movement was required to move to a particular target. This may be based on some explicit rule, or perhaps a visual image or blueprint (representation), of what was “correct”. In some ways, this should not be too surprising. The physical practice participant feels a discrepancy between their hand and the visual feedback and hence the error signal would generate an implicit correction to better align the felt consequences with the visual consequences. For an observer, the only discrepancy is between the seen position of the hand and the actual visual consequences. In observational learning, the observer does not act nor do they receive response-produced feedback associated with acting. There is evidence that a person with below neck peripheral neuropathy, which prevents any sensation associated with proprioception, also shows after-effects in these tasks (Bernier, Chua, Bard & Franks, 2006). This would imply that it is not the absence of proprioceptive feedback which prevents adaptation-induced after-effects. Rather, it is the absence of sending of motor commands and the generation of the efference associated with movement and the associated prediction of expected sensory consequences of that movement that prevents this type of sensory-motor updating. Although there are of course limits in applying research from this type of paradigm to observational learning of sport skills, the important message is that observational learning is not a direct-mediated process whereby we can acquire skills based on the same processes as engaged in physical practice. Important components of physical action are missing, and although we may be able to learn from watching, what is acquired is qualitatively different to what is acquired from doing.

As a result of this first study and differences in conclusions about potential processes engaged in observational learning, we conducted further studies to replicate and understand what is learned from watching others in these tasks. In one study, we reasoned that if observational practice engages different processes for learning than occurs as a result of doing, we should not see interference between these two modes of practice if participants were asked to learn two concurrent, yet opposing versions of the task (Larssen, Ong & Hodges, 2012). This is in effect another test of after-effects, in as much as what is acquired in one environment should not interfere with the learning in a subsequent environment if they are acquired differently. As illustrated in **Figure 6**, we supported this hypothesis, showing that two concurrently physically practiced tasks (30° clockwise (CW), Task A, followed by 30° counterCW, Task B) interfered retroactively with performance of Task A (ActAll group, A7, A8). In contrast, physical practice of Task A, followed by observational practice of Task B did not lead to interference in Task A (ObsB, A7, A8). Importantly, this was despite the fact that Task B was learned well by observers when its performance was eventually tested (B7, B8). For comparison, the NoB control group, did the worst on the retention of Task B, as would be expected in the absence of any type of practice on this task, and the group that observed both A and B (ObsAll), showed intermediate levels of interference when tested on Task A and errors comparable to the ActAll group in retention of Task B. In addition to the conceptual ramifications of these data, this research suggests that there are potential memory benefits to be gained from learning skills in different mediums, which may make both skills more robust to potential interference effects. This is something that deserves attention in tasks that are more applicable to sport, such as learning different martial arts moves, potentially the first through primarily physical practice, the second through observational practice and then test conditions requiring the back-to-back or integrated production of both skills. This may be viewed as an example of contextual interference (e.g., Shea & Morgan, 1979); whereby watching and physical practice encourage separate, yet related visuo-motor representations. As an aside, my PhD student April Karlinsky, and I have been looking at something related to this in a test of contextual interference effects when paired individuals alternate physical practice and watching and we have shown some moderation of the CI effect (Karlinsky & Hodges, in review)

There are potentially two or three characteristics associated with physically performing that may be limiting implicitly mediated adaptation in observers. Testing of these processes underpinned the rationale for subsequent studies. In one study, observers were seated in the virtual environment watching videos played onto the actual surface where they would be moving. They were told to imagine themselves making movements by envisioning that the arm and hand they saw moving was their own. One other change we made to the procedures was to engage participants in active prediction. They were asked to try and predict the feedback trajectory associated with their hand movements and they were explicitly asked to predict hand location from the feedback after each practice block (Ong, Larssen & Hodges, 2012). As with previous studies, observers learned from watching when subsequently asked to perform in the rotated environment, but they still failed to show after-effects in the absence of physical practice. This was despite the fact that they were now active observers, immersed in the same environment as the physical practice people, asked to imagine themselves moving and on certain trials, required to estimate their movements based only on the rotated feedback (which should engage prediction processes, albeit in a more explicit fashion than feedforward processes). However, we did see relatively large after-effects in a group that only received a short amount of physical practice (on the prediction trials). This led us to think that the physical practice potentially changed how people learnt from observing on the observation trials.

Consistent with work by Calvo-Merino and colleagues (2005, 2006), we speculated that action experiences could change processes engaged during action observation. As such, we anticipated that any further learning encouraged just from watching, following a period of physical practice, could now potentially be mediated by the motor system as evidenced by after-effects. Therefore, we physically trained people to be good at the adaptation task, tested for after-effects in a normal environment, then we effectively "washed out" any after-effects associated with this prior practice (Lim et al., 2014). As noted above, small after-effects were still evidenced in these conditions and as such we compared two groups which had had previous practice, one that now watched 200 more observation trials and a control group that did nothing (rested for the same amount of time). We also tested a new group that did not have any prior physical practice. Despite our predictions, there was no significant increase in the size of the after-effects after (experience-based) observational practice and the observation group did not differ from the no-practice control. However, it was hard to determine whether any new learning had occurred as assessed in the adapted environment as they were already performing at a plateau before the observation phase.

As a result of practice issues related to plateaus in performance and the fact that we saw evidence of after-effects when physical practice was interspersed with observational practice, we conducted a recent study to address these issues and specifically evaluate how interspersed practice (observe and physical practice), impacts adaptation learning (Hodges, Ho, Larssen & Burnett, in preparation). In this study, participants practiced with observational practice or physical practice, for 25 trials only, before being transferred to the opposite condition. In between transfer, we tested for after-effects and also at the end of practice. A third group had interspersed physical and observation trials (every 5 trials) and a fourth control group had the same schedule as the interspersed group, but they just rested on observation trials (i.e., spaced practice). We also assessed retention on adaptation trials the next day. Again, prior physical practice did not appear to change the learning processes engaged during pure observation trials (even though here, moderations to after-effects were still possible). Although there was some evidence of larger after-effects as a result of interspersing physical and observational practice, rather than providing these in a blocked order, these after-effects were also evident in the “rest” control group, whose physical practice was spaced in a way to match the interspersed group. This would suggest that one of the advantages associated with interspersing physical and observational practice is that potentially more (implicit) learning can occur as a result of the physical practice, perhaps as a result of consolidation processes engaged during practice (see for example, Kim, Oh & Schweighofer, 2015 and Sing & Smith, 2010, who have shown beneficial effects of spacing on long-term adaptation). Observation was shown to lead to a greater build-up of explicit knowledge than just physical practice and there was evidence that the combined groups, particularly the interspersed group, performed more accurately in the adapted environment when later tested in a post-test (though not on a delayed retention test).

In summary, these data on observation and visuomotor adaptation show that observational learning is an effective technique for teaching people to move in adapted environments, because people can pick up strategies and/or form images (blueprints) and translate these experiences to improvements in later physical practice (see also McGregor, Cashaback & Gribble, 2016, who have shown that the somatosensory cortex plays a significant role in learning from observation). However, we did not show behavioural evidence that observational practice leads to a motor-based adaptation, nor that interspersing of physical and observational practice changes what is observed, even though we would expect a greater resonance with the observed action because of the action experiences. There was evidence that merely interspersing breaks in physical practice aids more implicit, motor-related processes, although the reasons for this are somewhat unclear. Because observation benefits the pick-up of strategic, more explicitly acquired processes, the recommendation would still be to intersperse demonstrations frequently between physical practice trials (see also Deakin & Proteau, 2000; Ong & Hodges, 2012; Weeks & Anderson, 2000), rather than just rest. It is surprising that schedules of observational and physical practice have not received more attention in the observational learning research, particularly as applied to the optimal acquisition of sport-related tasks.

One last point on this updating of motor processes as a result of observational practice. In one study, small after-effects were noted by a group of researchers who studied whether observers were sensitive to errors in observation (Ronchi, Revol, Katayama, Rossetti & Farnè, 2011). In this study, observers saw hands of another person (who was actually seated behind the observer and reaching around them), continually miss laterally placed targets. When the observer was then engaged in a reaching task (i.e., straight ahead reaching), there was evidence of small compensatory after-effects in the direction opposite to the reach error. Although these were small, and mostly observed during proprioceptively guided reaching without a target, we wondered whether motor-related processes, as expressed through behavioural after-effects, could be (more likely) activated in situations where “real” errors (mistakes) are observed. In our learning situations, participants are seeing “correct” (adapted) aiming and hence may be less likely to implicitly correct when passively observing. In contrast, when watching a mistake, this might lead to a more automatic adaptation process to correct for the error. Hence we are currently testing people in our adaptation paradigm, whilst watching correct and incorrect movements (which are matched for the degree of error). Our hypothesis would be that only after watching people make errors, should compensatory after-effects be observed (i.e., movements in the opposite direction to the observed hand movements).

It is also important to point out that in none of our adaptation studies to date have we measured neurophysiological responses (through EEG, fMRI or EMG/MEPs in response to TMS) that may show evidence of low-level resonance of the motor system during action observation. This would of course provide more direct evidence of its activation, though not necessarily its role in learning, unless these neurophysiological effects, particularly in MNS related areas were correlated to behavioural effects (see Brown, Wilson & Gribble, 2009; McGregor & Gribble, 2015, who have used such techniques to probe dynamic adaptation processes as a result of observing). One of our planned areas of inquiry is to study mu rhythm modulation (i.e., beta band desynchronization as determined from EEG) in response to both acting and watching (either errors or correct adaptation), to better probe motor-system activation processes during observational learning and their behavioural consequences, in addition to error-related potentials, ERPs, that index awareness and response to errors (e.g., Nieuwenhuis, Ridderinkhof, Blom, Band & Kok, 2001).

Summary and conclusions

Over the past 20 years, myself, colleagues and students have been studying how and what people learn from watching others and ways to potentially facilitate these processes. This has led to various approaches, heavily influenced by the theoretical frameworks and methods available at the time, to test processes engaged during action-observation. To date, my approach has been almost exclusively behavioural, partly as a result of resources (there are many other researchers better equipped to do neuroimaging studies due to free access to a scanner for example), but also partly driven by my belief (and that of my mentors), that well conducted behavioural studies can elucidate on the internal mechanisms underpinning quite complex human actions. One example of this is the cerebral specialization model of Digby Elliott and colleagues used to explain visuo-motor issues in people with Down syndrome. This was primarily based on a dichotic listening paradigm and RT data, preceding any neurophysiological measurements, even though it was a model of brain function (e.g., Weeks & Elliott, 1992). I have also been involved in work involving the auditory startle response (or start-react effect), work primarily led by Ian Franks at UBC, which can give illustrative information about processes occurring in advance of action execution (e.g., Maslovat, Hodges, Chua & Franks, 2011) as well as preparation processes involved in action-observation (Maslovat, Chua & Hodges, 2013).

The data from my research over the years has provided evidence about the efficacy of observational practice as a learning tool, for both quite complex, whole-body movements (such as those involved in cricket bowling or soccer kicking), to more simple actions that are involved in dart-throwing or 2D aiming in virtual environments. Although the tasks are important to consider when evaluating the applicability of these data, the main message has been consistent, almost regardless of the technique. We have shown that processes engaged during action-observation and physical practice, whilst sharing similarities, are qualitatively different with respect to important aspects. This may seem an obvious statement, given that in physical practice, there is the sending of a motor command, the associated corollary discharge and feedforward processes that accompany action in addition to response-produced inherent feedback. However, there has been a strong move to convince people that observational learning is the same, motor-driven process, as that of physical practice. Whilst there are some truths to this message in as much as there are overlapping areas in the brain which respond to both action and observation (as shown through AON/MNS studies), and behaviourally there is evidence that effects which seem to be predominantly motor, also show up after observation (e.g., CI effects, guidance effects; e.g., Blandin, Proteau & Alain, 1994), this does not mean we should make general assumptions about the equivalence of these processes for motor skill learning. Many skills cannot be acquired from just observation, observation encourages a more strategic type of learning in general, and observers are not privy to the types of error information afforded to physical practice participants (nor respond in the same way when observing errors in others). As such, the learning that takes place during observational practice does not appear to be at an internal/motor system level, based on the changes to motor maps or implicit predictive processes.

Although individuals learn from watching others, and this phenomenon is ubiquitous, it is important to know how this happens so that we can determine the conditions when it might not work (or not work as well), and conditions when other techniques (such as spacing of practice or imagery) might be more effective. Questions such as how interspersing of physical and observational practice change processes engaged during observation are important, as is knowing the functional implications of action-observation for such things as prediction of action effects. Although the focus in this review has been on short-term learning studies, I have been involved in many studies involving skilled or elite performers in sports and games. The marrying of these two approaches (i.e., study of short-term learning where there is control of practice experiences), coupled with expertise studies (where performance is a more valid indication of skill and long-term experience), has advantages in helping arrive at conclusions which have both internal and external validity. I hope to continue to move between these approaches to help determine what and how we learn from watching others and how we (best) acquire motor skills more broadly. Stay tuned for the 20 years from now sequel!

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References

Aglioti, S. M., Cesari, P., Romani, M., & Urgesi, C. (2008). Action anticipation and motor resonance in elite basketball players. *Nature Neuroscience, 11(9)*, 1109-1116.

Al-Abood, S. A., Davids, K., Bennett, S. J., Ashford, D., & Marin, M. M. (2001). Effects of manipulating relative and absolute motion information during observational learning of an aiming task. *Journal of Sports Sciences, 19(7)*, 507-520.

Bandura, A. (1971). *Psychological Modelling*. New York: Lieber-Antherton

Bandura, A. (1977). Self-efficacy: toward a unifying theory of behavioral change. *Psychological Review, 84(2)*, 191-215.

Bandura,A. (1989). Social Cognitive Theory. In R. Vasta (Ed.), *Annals of Child Development: Vol. 6. Theories of Child Development* (pp.1-60). Greenwich, CT: JAI Press.

Bekkering, H., Wohlschlager, A., & Gattis, M. (2000). Imitation of gestures in children is goal-directed. *Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 53*, 153-164.

Bernier, P. M., Chua, R., Bard, C., & Franks, I. M. (2006). Updating of an internal model without proprioception: a deafferentation study. *Neuroreport, 17(13)*, 1421-1425.

Bernstein, N. A., Latash, M. L., & Turvey, M. (1996). *Dexterity and its development*. Mahwah, NJ : LEA/Taylor & Francis.

Black, C. B., & Wright, D. L. (2000). Can observational practice facilitate error recognition and movement production? *Research Quarterly for Exercise & Sport*, *71*(4), 331-339.

Blakemore, S. J., & Decety, J. (2001). From the perception of action to the understanding of intention. *Nature Reviews Neuroscience, 2*, 561–567.

Blandin, Y., Lhuisset, L., & Proteau, L. (1999). Cognitive processes underlying observational learning of motor skills. *Quarterly Journal of Experimental Psychology: Section A, 52(4),* 957-979.

Blandin, Y., Proteau, L., & Alain, C. (1994). On the cognitive processes underlying contextual interference and observational learning. *Journal of Motor Behavior, 26(1),* 18-26.

Breslin, G, Hodges NJ, Williams, A.M., Curran, W., & Kremer, J. (2005). Modelling relative motion to facilitate intra-limb coordination. *Human Movement Science, 24*, 446 - 463.

Breslin, G., Hodges, N. J., Williams, A. M., Kremer, J., & Curran, W. (2006). A comparison of intra-and inter-limb relative motion information in modelling a novel motor skill. *Human Movement Science, 25(6),* 753-766.

Breslin, G., Hodges, N. J., Williams, A. M. (2009). The effect of information load and time on observational learning. *Research Quarterly for Exercise & Sport, 80 (3),* 480-490.

Broadbent, D.P., Causer, J., Williams, A.M., Ford, P.R. (2014). Perceptual-cognitive skill training and its transfer to expert performance in the field: Future research directions. *European Journal of Sport Science,15(4),* 322-331.

Brown, L.E., Wilson, E.T., & Gribble, P.L. (2009). Repetitive transcranial magnetic stimulation to the primary motor cortex interferes with motor learning by observing. *Journal of Cognitive Neuroscience, 21(5),*1013-1022.

Buchanan, J. J., & Dean, N. (2014). Consistently modeling the same movement strategy is more important than model skill level in observational learning contexts. *Acta Psychologica, 146*, 19-27.

Buchanan, J. J., & Park, I. (2017). Observation and physical practice: different practice contexts lead to similar outcomes for the acquisition of kinematic information. *Psychological Research, 81(1)*, 83-98.

Buchanan, J. J., Ryu, Y. U., Zihlman, K., & Wright, D. L. (2008). Observational practice of relative but not absolute motion features in a single-limb multi-joint coordination task. *Experimental Brain Research, 191(2)*, 157-169.

Calvo-Merino, B., Glaser, D.E., Grezes, J., Passingham, R.E., & Haggard, P. (2005). Action observation and acquired motor skills: An fMRI study with expert dancers. *Cerebral Cortex, 15*, 1243-1249.

Calvo-Merino, B., Grezes, J., Glaser, D.E., Passingham, R.E., & Haggard, P. (2006). Seeing or doing? Influence of visual and motor familiarity in action observation. *Current Biology, 16*, 1905-1910.

Carroll, W. R., & Bandura, A. (1982). The role of visual monitoring in observational learning of action patterns: Making the unobservable observable. *Journal of Motor Behavior*, *14*(2), 153-167.

Carroll, W. R., & Bandura, A. (1990). Representational guidance of action production in observational learning: A causal analysis. *Journal of Motor Behavior*, *22*(1), 85-97.

Caspers S., Zilles, K., Laird, A.R., Eickhoff, S.B. (2010) ALE meta-analysis of action observation and imitation in the human brain. *Neuroimage, 50*, 1148–1167.

Cattaneo, L. & Rizzolatti, G. (2009). The mirror neuron system. *Archives of Neurology, 66*(5), 557-560.

Cross, E.S., Kraemer, D.J., Hamilton, A.F., Kelley, W.M., Grafton, S.T. (2009) Sensitivity of the action observation network to physical and observational learning. *Cerebral Cortex*, *19,* 315–326.

Cutting, J. E. & Proffitt, D. R. (1982). The minimum principle and the perception of absolute, common and relative motion. *Cognitive Psychology, 14*, 211-46.

Davids, K., Button, C., & Bennett, S.J., (2008). *Dynamics of Skill Acquisition: A Constraints-Led Approach*. Human Kinetics

Deakin, J. M., & Proteau, L. (2000). The role of scheduling in learning through observation. *Journal of Motor Behavior, 32(3)*, 268-276.

Eaves, D., Hodges, N.J., & Williams, A.M. (2008). Energetic costs of incidental visual coupling during treadmill running. *Medicine & Science in Sport & Exercise, 40(8),* 1506-1514.

Feltz, D. L., Landers, D. M., & Raeder, U. (1979). Enhancing self-efficacy in high-avoidance motor tasks: A comparison of modeling techniques. *Journal of Sport Psychology, 1(2),* 112-122.

Fontaine, R. J., Lee, T. D., & Swinnen, S. P. (1997). Learning a new bimanual coordination pattern: Reciprocal influences of intrinsic and to-be-learned patterns. *Canadian Journal of Experimental Psychology, 51(1),* 1-9.

Ford, P., Hodges, N. J., Huys, R., & Williams, A. M. (2006). The role of external action-effects in the execution of a soccer kick: a comparison across skill level. *Motor Control, 10(4),* 386-404.

Ford, P., Hodges, N. J., & Williams, A. M. (2007). Examining action effects in the execution of a skilled soccer kick by using erroneous feedback. *Journal of Motor Behavior, 39(6),* 481-490.

Ford, P., Hodges, N. J., Huys, R., & Williams, A. M. (2009). An evaluation of end-point trajectory planning during skilled kicking. *Motor Control, 13(1),* 1-24.

Gallese, V., Keysers, C., & Rizzolatti, G. (2004). A unifying view of the basis of social cognition. *Trends in Cognitive Science, 8*, 396–403.

Gardner, T., Goulden, N., & Cross, E. S. (2015). Dynamic modulation of the action observation network by movement familiarity. *Journal of Neuroscience, 35*(4), 1561-1572.

Gazzola V., & Keysers, C. (2009). The observation and execution of actions share motor and somatosensory voxels in all tested subjects: single-subject analyses of unsmoothed fMRI data. *Cerebral Cortex, 19,* 1239–1255

Gentile, A. M. (1972). A working model of skill acquisition with application to teaching. *Quest, 17(1),* 3-23.

Gibson, J. J. (1979 /1986). *The Ecological Approach to Visual Perception*. LEA.

Gibson, E. J. (2000). Where is the information for affordances? *Ecological Psychology, 12(1)*, 53-56.

Hayes, S. J., Hodges, N. J., Horn, R.R., Scott, M.A., & Williams, A.M. (2006). Scaling a motor skill through observation and practice. *Journal of Motor Behavior, 38*, 357 - 366.

Hayes, S. J., Hodges, N. J., Huys, R., & Williams, A. M. (2007). End-point focus manipulations to determine what information is used during observational learning. *Acta Psychologica, 126(2),* 120-137.

Hayes, S. J., Hodges, N. J., Scott, M.A., Horn, R.R., & Williams, A.M. (2007). The efficacy of demonstrations in teaching children an unfamiliar movement skill: the effects of object orientated actions and point-light demonstrations. *Journal of Sports Sciences, 25*, 559-575.

Hodges, N. J., Chua, R., & Franks, I. M. (2003). The role of video in facilitating perception and action of a novel coordination movement. *Journal of Motor Behavior, 35*(3), 247-260.

Hodges, N. J., & Coppola, T. (2015). What we think we learn from watching others: the moderating role of ability on perceptions of learning from observation. *Psychological Research*, *79*(4), 609-620.

Hodges, N. J., & Franks, I. M. (2000). Attention focusing instructions and coordination bias: Implications for learning a novel bimanual task. *Human Movement Science, 19(6),* 843-867.

Hodges, N. J., & Franks, I. M. (2001). Learning a coordination skill: Interactive effects of instruction and feedback. *Research Quarterly for Exercise and Sport, 72(2),* 132-142.

Hodges, N. J., & Franks, I. M. (2002a). Learning as a function of coordination bias: building upon pre-practice behaviours. *Human Movement Science, 21(2)*, 231-258.

Hodges, N. J., & Franks, I. M. (2002b). Modelling coaching practice: the role of instruction and demonstration. *Journal of Sports Sciences, 20(10)*, 793-811.

Hodges, N. J., & Franks, I. M. (2004a). Instructions, demonstrations and the learning process: Creating and constraining movement options. In A.M. Williams & N.J. Hodges (Eds), *Skill Acquisition in Sport: Research, Theory and Practice* (pp145-174). London: Routledge.

Hodges, N. J., & Franks, I. M. (2004b). The nature of feedback. In M. Hughes & I.M. Franks (Eds). *Notation Analysis of Sport* (pp 17-39). London, Routledge.

Hodges, N. J., & Franks, I. M. (2008). The provision of information. In M. Hughes & I.M. Franks (Eds). *Essentials of Performance Analysis: An Introduction* (pp21-39). London: Routledge.

Hodges, N. J., Hayes, S. J., Breslin, G. & Williams, A.M. (2005). An evaluation of the minimal constraining information during movement observation and reproduction. *Acta Psychologica, 119*, 264 - 282.

Hodges, N. J., Hayes, S. J., Eaves, D. L., Horn, R. R., & Williams, A. M. (2006). End-point trajectory matching as a method for teaching kicking skills. *International Journal of Sport Psychology, 37(2)*, 230-247.

Hodges, N.J., Ho, D., Larssen, B., & Burnett, T. (in prep). *Determining observational practice effects for visuo-motor adaptation learning when interspersed with physical practice*.

Hodges, N. J., & Lee, T. D. (1999). The role of augmented information prior to learning a bimanual visual-motor coordination task: Do instructions of the movement pattern facilitate learning relative to discovery learning?. *British Journal of Psychology*, *90*(3), 389-404.

Hodges, N. J., Starkes, J. L., & MacMahon, C. (2006). Expert Performance in Sport: A Cognitive Perspective. In N. Charness, K.A. Ericsson, R.R. Hoffman & P. Feltovich (Eds). *Cambridge Handbook of Expertise* (pp471 – 488). NY: Cambridge University Press.

Hodges, N.J., Williams, A.M., Hayes, S.J., Breslin, G. (2007). What is modeled during observational learning? *Journal of Sports Sciences*, *25*, 531 – 545.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences, 24*, 849–937.

Horn, R. R., Williams, A. M., Scott, M. A., & Hodges, N. J. (2005). Visual search and coordination changes in response to video and point-light demonstrations without KR. *Journal of Motor Behavior, 37(4)*, 265.

Jeannerod, M. (1994). The representing brain: neural correlates of motor intention and imagery. *Behavioural & Brain Sciences, 17*, 187–245.

Johansson, G. (1973). Visual perception of biological motion and a model for its analysis. *Perception and Psychophysics, 14*, 201-211.

Karlinsky, A., & Hodges, N.J. (in review). Dyad practice impacts self-directed practice behaviours and motor learning outcomes in a contextual interference paradigm. *Journal of Motor Behavior*

Karlinsky, A., Zentgraf, K. & Hodges, N.J. (in review). Action-skilled observation: Issues for the study of sport-expertise and the brain. *Progress in Brain Research.*

Kelso, J. A. (1984). Phase transitions and critical behavior in human bimanual coordination. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *246*(6), R1000-R1004.

Kelso, J. S. (1997). *Dynamic patterns: The Self-Organization of Brain and Behavior*. MIT press.

Kim, S., Oh, Y., & Schweighofer, N. (2015). Between-trial forgetting due to interference and time in motor adaptation. *PLoS ONE 10(11)*: e0142963.

Koch, I., Keller, P., & Prinz, W. (2004). The ideomotor approach to action control: Implications for skilled performance. *International Journal of Sport & Exercise Psychology, 2,* 362-375.

Krakauer, J. W., & Shadmehr, R. (2006). Consolidation of motor memory. *Trends in Neurosciences, 29(1)*, 58-64.

Kruger, J., & Dunning, D. (1999). Unskilled and unaware of it: how difficulties in recognizing one's own incompetence lead to inflated self-assessments. *Journal of Personality & Social Psychology, 77(6)*, 1121.

Kugler, P.N., Kelso, J.A.S., & Turvey, M.T. (1982). On the control and co-ordination of naturally developing systems. In J.A.S. Kelso & J.E. Clark (Eds.), *The Development of Movement Control and Co-ordination* (pp. 5-78). New York: Wiley.

Larssen, B. C., Ong, N. T., & Hodges, N. J. (2012). Watch and learn: seeing is better than doing when acquiring consecutive motor tasks. *PloS one, 7(6),* e38938.

Latash, M.L., Scholz, J.P. & Schoner, G. (2002). Motor control strategies revealed in the structure of motor variability. *Exercise & Sport Science Reviews, 30(1),* 26–31.

Lee, D. N. (1998). Guiding movement by coupling taus. *Ecological psychology, 10(3),* 221-250.

Lee, D. N., Lishman, J. R., & Thomson, J. A. (1982). Regulation of gait in long jumping. *Journal of Experimental Psychology: Human Perception & Performance, 8(3),* 448.

Lim, S. B., Larssen, B. C., & Hodges, N. J. (2014). Manipulating visual–motor experience to probe for observation-induced after-effects in adaptation learning. *Experimental Brain Research, 232(3),* 789-802.

Mann, D. T., Williams, A. M., Ward, P., & Janelle, C. M. (2007). Perceptual-cognitive expertise in sport: A meta-analysis. *Journal of Sport & Exercise Psychology, 29(4),* 457-478.

Maslovat, D. (2010). *Motor preparation changes with practice* (Doctoral dissertation, University of British Columbia) (https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0071483).

Maslovat, D., Chua, R., & Hodges, N.J. (2013). When unintended movements "leak" out: A startling acoustic stimulus can elicit a prepared response during motor imagery and action observation. *Neuropsychologia, 51,* 838-844.

Maslovat, D., Hayes, S. J., Horn, R., & Hodges, N. J. (2010). Motor learning through observation. In D. Elliott & M.A Khan (Eds). *Vision and Goal-directed movement: Neurobehavioural perspectives* (pp315-340). Champaign, IL: Human Kinetics.

Maslovat, D., Hodges, N.J., Chua, R., & Franks, I.M. (2011). Motor preparation and the effects of practice: Evidence from startle. *Behavioural Neuroscience, 125 (2),* 226-240.

Maslovat, D., Hodges, N. J., Krigolson, O. E., & Handy, T. C. (2010). Observational practice benefits are limited to perceptual improvements in the acquisition of a novel coordination skill. *Experimental Brain Research, 204(1),* 119-130.

Mataric, M.J., & Pomplun, M. (1998). Fixation behavior in observation and imitation of human movement. *Cognitive Brain Research, 7*, 191-202.

Mather, G., Radford, K., & West, S. (1992). Low-level visual processing of biological motion. *Proceedings of the Royal Society of London B: Biological Sciences, 249(1325)*, 149-155.

Mattar, A. A., & Gribble, P. L. (2005). Motor learning by observing. *Neuron, 46(1),* 153-160.

McCullagh, P., & Meyer, K. N. (1997). Learning versus correct models: Influence of model type on the learning of a free-weight squat lift. *Research Quarterly for Exercise & Sport, 68(1)*, 56-61.

McGarry, T. I. M., Khan, M. A., & Franks, I. M. (1999). On the presence and absence of behavioural traits in sport: An example from championship squash match-play. *Journal of Sports Sciences*, *17*(4), 297-311.

McGregor, H.R., & Gribble, P.L. (2015). Changes in Visual and Sensory-Motor Resting-State Functional Connectivity Support Motor Learning by Observing. *Journal of Neurophysiology, 114*, 677-688.

McGregor, H.R., Cashaback, J.G., Gribble, P.L. (2016) Functional plasticity in somatosensory cortex supports motor learning by observing. *Current Biology 26(7),* 921-927.

Memmert, D. (2009). Pay attention! A review of visual attentional expertise in sport. *International Review of Sport and Exercise Psychology, 2(2)*, 119-138.

Miall, R. C., & Wolpert, D. M. (1996). Forward models for physiological motor control. *Neural Networks, 9(8)*, 1265-1279.

Morasso, P. (1981). Spatial control of arm movements. *Experimental Brain Research, 42(2),* 223-227.

Müller, S., & Abernethy, B. (2012). Expert anticipatory skill in striking sports: A review and a model. *Research Quarterly for Exercise and Sport, 83(2),*175-187.

Mulligan, D., & Hodges, N. J. (2014). Throwing in the dark: improved prediction of action outcomes following motor training without vision of the action. *Psychological Research*, *78*(5), 692-704.

Mulligan, D., Lohse, K. R., & Hodges, N. J. (2016a). An action-incongruent secondary task modulates prediction accuracy in experienced performers: evidence for motor simulation. *Psychological Research*, *80*(4), 496-509.

Mulligan, D., Lohse, K. R., & Hodges, N. J. (2016b). Evidence for dual mechanisms of action prediction dependent on acquired visual-motor experiences. *Journal of Experimental Psychology: Human Perception and Performance, 42(10),* 1615-1626.

Mulligan, D., & Hodges, N.J. (2016). Evidence against the automaticity of motor simulation in action prediction: Separately acquired visual-motor and visual representations can be used flexibly to aid in prediction accuracy. *Journal of Exercise, Movement & Sport, 48* (SCAPPS. Waterloo, Canada).

Newell, K. M. (1985). Coordination, control and skill. *Advances in Psychology, 27,* 295-317.

Nieuwenhuis, S., Ridderinkhof, K. R., Blom, J., Band, G. P., & Kok, A. (2001). Error-related brain potentials are differentially related to awareness of response errors: Evidence from an antisaccade task. *Psychophysiology*, *38*(5), 752-760.

Ong, N. T., & Hodges, N. J. (2010). Absence of after-effects for observers after watching a visuomotor adaptation. *Experimental Brain Research*, *205*(3), 325-334.

Ong, N. T., & Hodges, N. J. (2012). Mixing it up a little. How to schedule observational practice. In N.J. Hodges & A.M. Williams (Eds). *Skill Acquisition in Sport: Research, Theory & Practice (2nd edition)* (pp22-39). London: Routledge.

Passos, P., Araújo, D., Davids, K., Gouveia, L., Milho, J., & Serpa, S. (2008). Information-governing dynamics of attacker-defender interactions in youth rugby union. *Journal of Sports Sciences, 26*, 1421–1429.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology, 9,* 129-154.

Redding, G. M., & Wallace, B. (1996). Adaptive spatial alignment and strategic perceptual-motor control. *Journal of Experimental Psychology: Human Perception and Performance, 22(2),* 379.

Redding, G. M., & Wallace, B. (2002). Strategic calibration and spatial alignment: a model from prism adaptation. *Journal of Motor Behavior, 34(2),* 126-138.

Renshaw, I., Davids, K., Savelsbergh, G.J.P. (2010). *Motor Learning in Practice: A Constraints-Led Approach*. London: Routledge.

Rizzolatti, G., & Craighero, L. (2004). The mirror-neuron system. *Annual Reviews in Neuroscience, 27,* 169-192.

Rizzolatti G., Fogassi, L., Gallese V. (2001) .Neurophysiological mechanisms underlying the understanding and imitation of action. *Nature Reviews Neuroscience, 2,* 661–670.

Rizzolatti, G., Fogassi, L., & Gallese, V. (2006). Mirrors in the Mind. *Scientific American, 295,* 30–37.

Ronchi, R., Revol, P., Katayama, M., Rossetti, Y., & Farnè, A. (2011). Seeing your error alters my pointing: observing systematic pointing errors induces sensori-motor after-effects. *PloS One, 6(6),* e21070.

Rosenthal, T. L., & Bandura, A. (1978). Psychological modeling: Theory and practice. In S.L. Garfield & S.E. Bergin (Eds), *Handbook of Psychotherapy and Behavior Change: An Empirical Analysis, 2nd ed,* (pp621-658). NY: Wiley.

Rumiati, R.I., Weiss, P.H., Tessari, A., Assmus, A., Zilles, K., Herzog, H., & Fink, G.R. (2005). Common and differential neural mechanisms supporting imitation of meaningful and meaningless actions. *Journal of Cognitive Neuroscience, 17*, 1420-1431.

Runeson, S. & Frykolm, G. (1983). Kinematic specification of dynamics as an informational basis for person-and-action perception. *Journal of Experimental Psychology: General, 112*, 589-615.

Scheidt, R. A., Reinkensmeyer, D. J., Conditt, M. A., Rymer, W. Z., & Mussa-Ivaldi, F. A. (2000). Persistence of motor adaptation during constrained, multi-joint, arm movements. *Journal of Neurophysiology, 84(2)*, 853-862.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82(4)*, 225.

Schubotz, R. I. (2007). Prediction of external events with our motor system: towards a new framework. *Trends in Cognitive Sciences, 11(5)*, 211-218.

Schütz-Bosbach, S., & Prinz, W. (2007). Perceptual resonance: action-induced modulation of perception. *Trends in Cognitive Sciences*, 11(8), 349-355.

Scully, D., & Carnegie, E. (1998). Observational learning in motor skill acquisition: A look at demonstrations. *The Irish Journal of Psychology, 19(4)*, 472-485.

Scully, D. M., & Newell, K. M. (1985). Observational-Learning and the Acquisition of Motor-Skills-toward a Visual-Perception Perspective. *Journal of Human Movement Studies, 11(4)*, 169-186.

Shadmehr, R., Smith, M. A., & Krakauer, J. W. (2010). Error correction, sensory prediction, and adaptation in motor control. *Annual Review of Neuroscience, 33*, 89-108.

Shea, J. B., & Morgan, R. L. (1979). Contextual interference effects on the acquisition, retention, and transfer of a motor skill. *Journal of Experimental Psychology: Human Learning & Memory, 5(2)*, 179.

Sing, G. C., & Smith, M. A. (2010). Reduction in learning rates associated with anterograde interference results from interactions between different timescales in motor adaptation. *PLoS Computational Biology, 6(8),* e1000893.

Smith, D. M. (2016). Neurophysiology of action anticipation in athletes: A systematic review. *Neuroscience & Biobehavioral Reviews, 60*, 115-120.

Springer, A., Parkinson, J. & Prinz, W. (2013). Action simulation: time course and representational mechanisms. *Frontiers in Psychology, 4*.

Stadler, W., Schubotz, R. I., von Cramon, D. Y., Springer, A., Graf, M., & Prinz, W. (2011). Predicting and memorizing observed action: differential premotor cortex involvement. *Human Brain Mapping, 32(5),* 677-687.

Swinnen, S. P. (2002). Intermanual coordination: from behavioural principles to neural-network interactions. *Nature Reviews Neuroscience, 3(5),* 348-359.

Swinnen, S. P., Dounskaia, N., Walter, C. B., & Serrien, D. J. (1997). Preferred and induced coordination modes during the acquisition of bimanual movements with a 2: 1 frequency ratio. *Journal of Experimental Psychology: Human Perception & Performance, 23(4),* 1087-1110.

Swinnen, S. P., Lee, T. D., Verschueren, S., Serrien, D. J., & Bogaerds, H. (1997). Interlimb coordination: Learning and transfer under different feedback conditions. *Human Movement Science, 16(6),* 749-785.

Swinnen, S. P., & Wenderoth, N. (2004). Two hands, one brain: cognitive neuroscience of bimanual skill. *Trends in Cognitive Sciences, 8(1),* 18-25.

Tomeo, E., Cesari, P., Aglioti, S. M., & Urgesi, C. (2013). Fooling the kickers but not the goalkeepers: behavioral and neurophysiological correlates of fake action detection in soccer. *Cerebral Cortex, 23 (11)*, 2765-2778.

Tsutsui, S., Lee, T. D., & Hodges, N. J. (1998). Contextual interference in learning new patterns of bimanual coordination. *Journal of Motor Behavior, 30(2)*, 151-157.

Urgesi, C., Maieron, M., Avenanti, A., Tidoni, E., Fabbro, F., & Aglioti, S. M. (2010). Simulating the future of actions in the human corticospinal system. *Cerebral Cortex, 20(11)*, 2511-2521.

Vogt, S., & Thomaschke, R. (2007). From visuo-motor interactions to imitation learning: Behavioural and brain imaging studies. *Journal of Sports Sciences, 25*, 3-23.

Weeks, D. L., & Anderson, L. P. (2000). The interaction of observational learning with overt practice: Effects on motor skill learning. *Acta Psychologica, 104(2)*, 259-271.

Weeks, D. J., & Elliott, D. (1992). Atypical cerebral dominance in Down's syndrome. *Bulletin of the Psychonomic Society, 30(1)*, 23-25.

Weiss, M. R., Ebbeck, V., Rose, D.J. (1992). "Show and tell" in the gymnasium revisited: Developmental differences in modeling and verbal rehearsal effects on motor skill learning and performance. *Research Quarterly for Exercise & Sport. 63 (3)*, 292–301.

Williams, A.M., Hodges, N.J., North, J., Barton, G. (2006). Perceiving patterns of play in dynamic sport tasks: Investigating the essential information underlying skilled performance. Perception, 35, 317 - 332.

Williams, M., & Davids, K. (1995). Declarative knowledge in sport: A by-product of experience or a characteristic of expertise? *Journal of Sport & Exercise Psychology, 17(3)*, 259-275.

Wilson, A. D., & Bingham, G. P. (2008). Identifying the information for the visual perception of relative phase. *Perception & Psychophysics, 70(3)*, 465-476.

Wilson, A. D., Collins, D. R., & Bingham, G. P. (2005). Perceptual coupling in rhythmic movement coordination: stable perception leads to stable action. *Experimental Brain Research, 164(4),* 517-528.

Wishart, L. R., Lee, T. D., Murdoch, J. E., & Hodges, N. J. (2000). Effects of aging on automatic and effortful processes in bimanual coordination. *The Journals of Gerontology Series B: Psychological Sciences & Social Sciences, 55(2)*, P85-P94.

Wolpert, D. M. (1997). Computational approaches to motor control. *Trends in Cognitive Sciences, 1(6)*, 209-216.

Wolpert, D. M., Diedrichsen, J., & Flanagan, J. R. (2011). Principles of sensorimotor learning. *Nature Reviews Neuroscience, 12(12)*, 739-751.

Wolpert, D. M., Ghahramani, Z., & Flanagan, J. R. (2001). Perspectives and problems in motor learning. *Trends in Cognitive Sciences, 5(11)*, 487-494.

Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science, 269(5232),* 1880-1882.

Zanone, P. G., & Kelso, J. A. (1992). Evolution of behavioral attractors with learning: nonequilibrium phase transitions. *Journal of Experimental Psychology: Human Perception & Performance, 18(2),* 403.

Zanone, P. G., & Kelso, J. S. (1997). Coordination dynamics of learning and transfer: collective and component levels. *Journal of Experimental Psychology Human Perception & Performance, 23(5)*, 1454.

Zentgraf, K., Munzert, J., Bischoff, M., & Newman-Norlund, R. D. (2011). Simulation during observation of human actions–theories, empirical studies, applications. *Vision Research, 51(8)*, 827-835.

Figure captions

Figure 1: “Schematic display of apparatus set-up and design including location of monitor, speakers, and manipulanda (midpoint table markers not shown). The *X* indicates the location of the observer during acquisition trials”. Reproduced from Maslovat, D., Hodges, N. J., Krigolson, O. E., & Handy, T. C. (2010). Observational practice benefits are limited to perceptual improvements in the acquisition of a novel coordination skill. *Experimental Brain Research, 204*(1), 119-130, with permission of Springer.

Figure 2. Figure 2a shows *“A*ngle-angle plots for the mean shoulder-elbow coordination profile in early (A and C) and late (B and D) practice for the adult group that watched a video model (A and B) and the adult group that watched a point-light model (C and D) groups (open circles denote the model’s trace).” Figure reproduced from Hayes, S. J., Hodges, N. J., Scott, M. A., Horn, R. R., & Williams, A. M. (2007). The efficacy of demonstrations in teaching children an unfamiliar movement skill: The effects of object-orientated actions and point-light demonstrations. *Journal of Sports Sciences*, *25*(5), 559-575. Available online: http://www.tandfonline.com/doi/full/10.1080/02640410600947074?src=recsys. Figure 2b shows an example of the video and point light display (PLD) model (3 static clips, although this was presented as dynamic, continuous footage) used in the Hayes et al. (2007) experiments in which the angle-angle plots shown in 2b were derived.

Figure 3: Figure 3a details the typical procedures used across various studies we have conducted using the dart prediction task. The training phase typically lasts 2 days and in recent studies, we have switched from physical/motor practice on day 1 to perceptual training on day 2 (or v.v.). The motor task typically involves a restricted number of trials throwing to a dart board, either aiming for the bullseye (centre) or for the top, middle or bottom sections. The procedures for the pre-test are repeated after training in the post-test (t = trials). In Figure 3b, “Trial presentation: all video sequences included an initial dart preparation/set-up phase which lasted ~2 s. Depending on the condition the participant would then see an additional one to four frames (33–132 ms), corresponding to the four temporal occlusion points. The final frame would remain on the screen for 2 s after which point 2 prompt screens would be presented, requesting a predictive decision from the participant (top, middle or bottom) as well as a rating of confidence” Reproduced from Mulligan, D., Lohse, K. R., & Hodges, N. J. (2016a). An action-incongruent secondary task modulates prediction accuracy in experienced performers: evidence for motor simulation. *Psychological Research*, *80*(4), 496-509, with permission of Springer.

Figure 4: Percentage accuracy on the dart prediction task as a function of skill group (novice, skilled), occlusion frame (1-4, as described in Fig 3b above) and secondary task condition (no secondary task, tone monitoring, pressing against a force gauge with the right/throwing arm, or mimicking the observed action, holding, but not throwing a dart). Data from Mulligan, Lohse & Hodges (2016a).

Figure 5: Equipment set-up for visuo-motor adaptation experiments (left) and sample target displays for 3 variations of the visuo-motor task (right); a) illustrates “normal” aiming where the hand (dashed line indicates hand trajectory) and cursor (green line indicates cursor trajectory) go

to the same target. Normal aiming is often performed without cursor feedback and vision of the hand. In b), adapted aiming is illustrated. The hand moves to a location that is 30° counter-clockwise (CCW) to the target, such that the cursor hits the target due to a 30° CW rotation. In c), after-effects are illustrated. When the actor is asked to aim to target 3 under known "normal" aiming conditions, a bias to the right (CCW) of the target is shown. Note, in test of after-effects, cursor feedback is not provided, but is shown here only for illustration. This figure is adapted from Lim, S. B., Larssen, B. C., & Hodges, N. J. (2014). Manipulating visual–motor experience to probe for observation-induced after-effects in adaptation learning. *Experimental Brain Research*, *232*(3), 789-802. https://link.springer.com/article/10.1007/s00221-013-3788-6, with permission of Springer.

Figure 6: "Performance error as a function of experimental group and practice phase. Mean directional constant error (degrees) as a function of block for the ActAll (ActA & ActB), ObsB (ActA, ObsB), ObsAll (ObsA & ObsB) and NoB (ActA, noB) groups in normal environment pre-tests (P1, P2), across physical practice of Task A (clockwise rotation, A1–A6) and Task B (counterclockwise rotation, B1–B6) and in tests of retention of Tasks A (A7, A8) and B (B7, B8)". Figure adapted from Larssen BC et al. (2012) Watch and learn: seeing is better than doing when acquiring consecutive motor tasks. *PLOS One*, *7*(6), e38938. doi:10.1371/journal.pone.0038938

Figure 1

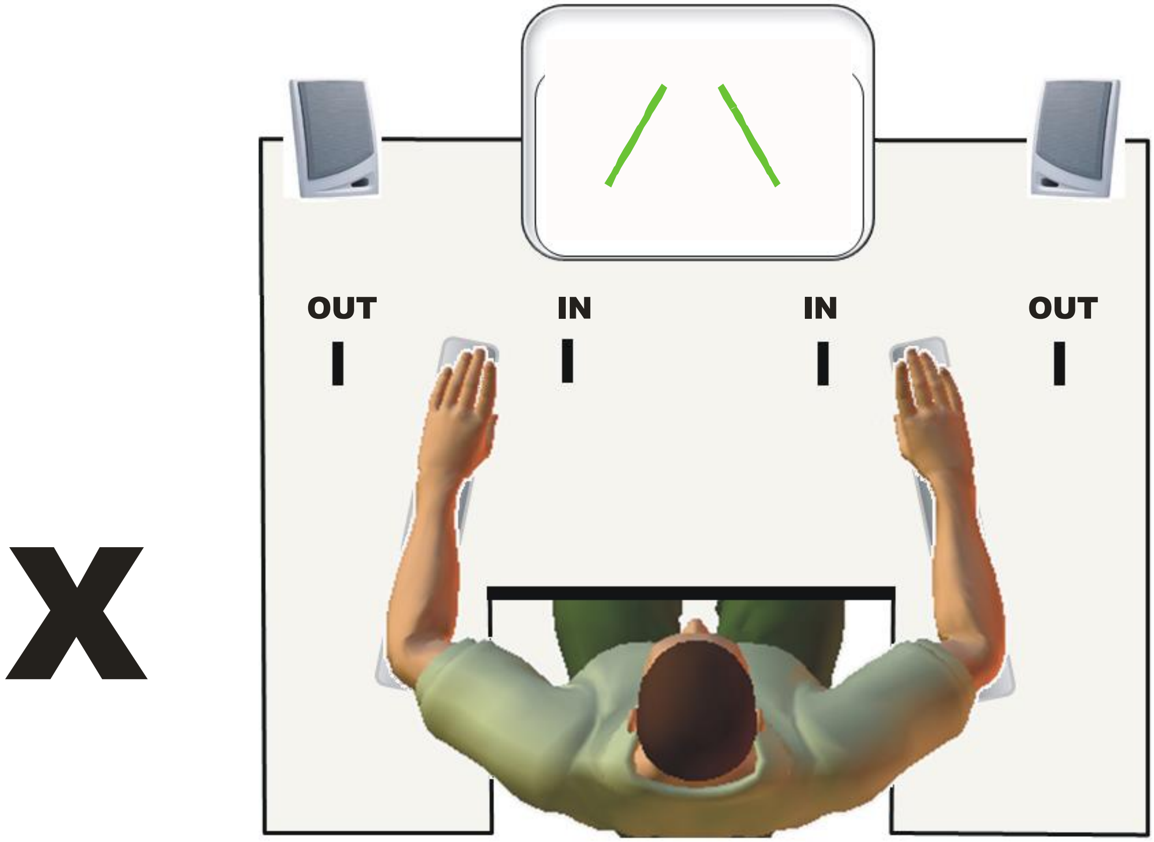
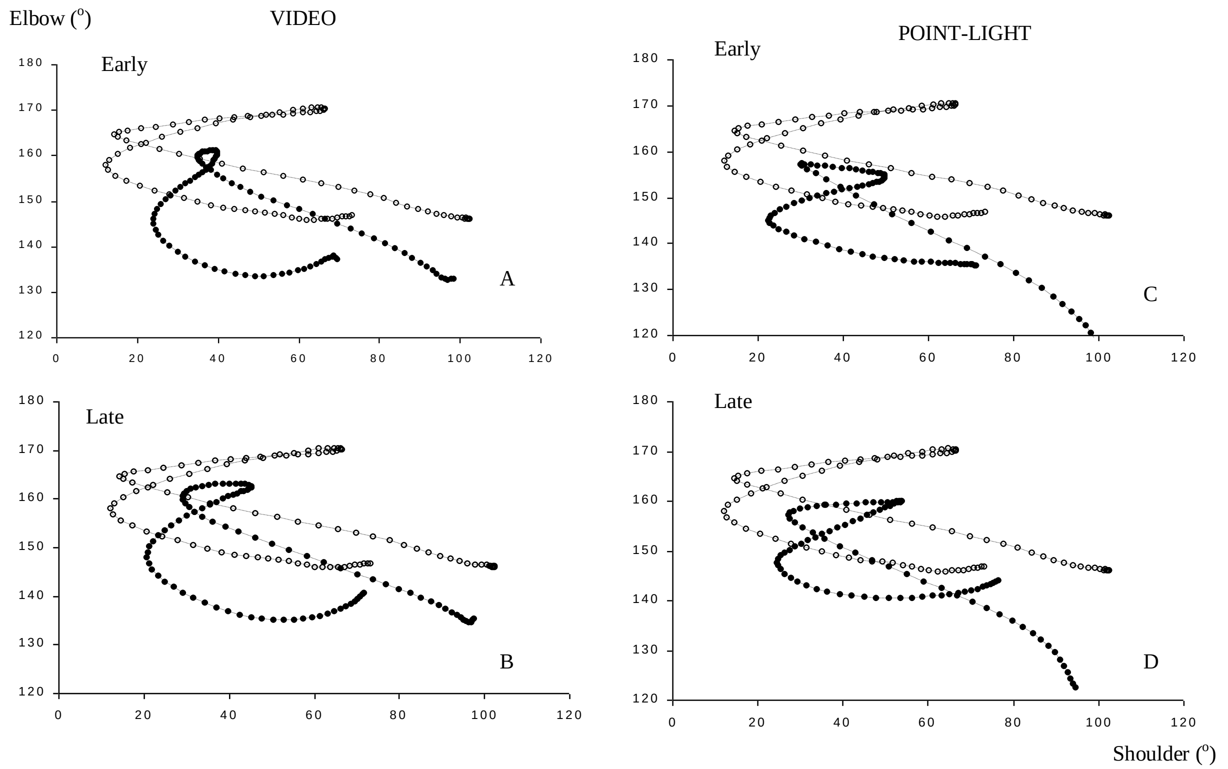
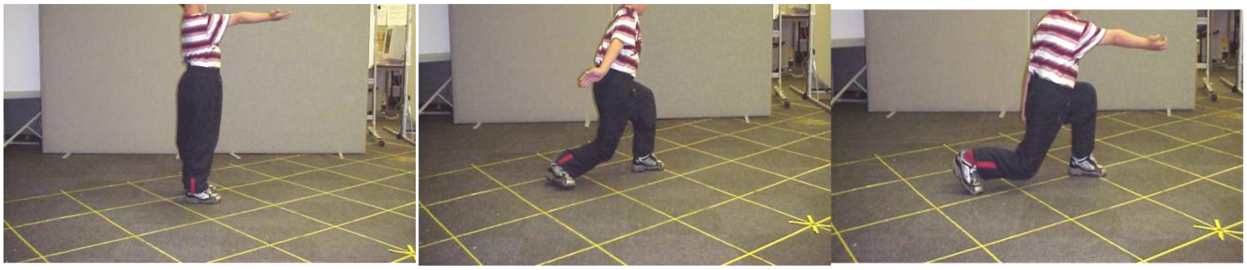


Figure 2

a)

b)





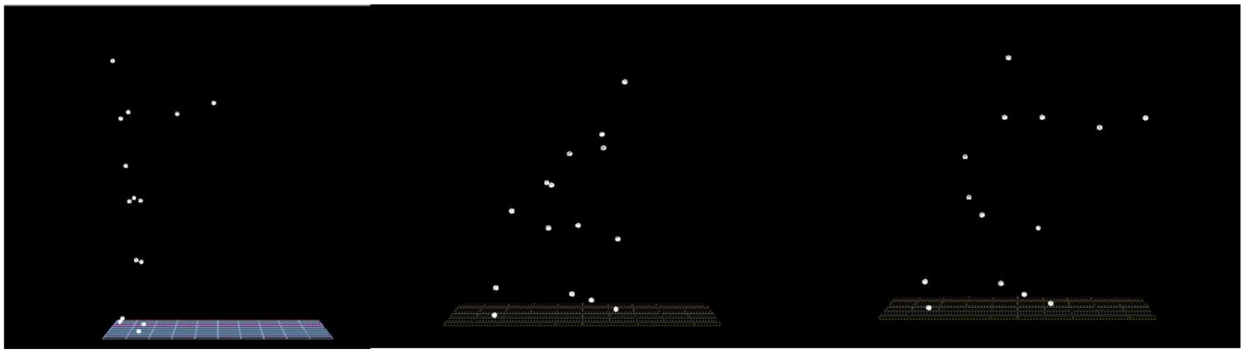


Figure 3

a)

Pre-test (D1)		Training phase (1 or 2 days)	Post-tests (end of D1 &/or D2)	
Motor task	**Prediction task**	**Motor, visual, none**	**Prediction task**	**Motor task**
Throw darts	Occluded video	Physical practice	Occluded video	Throw darts
	4 Dual-task conditions	Observational practice	4 Dual-task conditions	
		Perceptual/prediction training		
	No feedback	With feedback	No feedback	
t = 9	t = 36/cond	t = 135-270	t = 36/cond	t = 9

b)

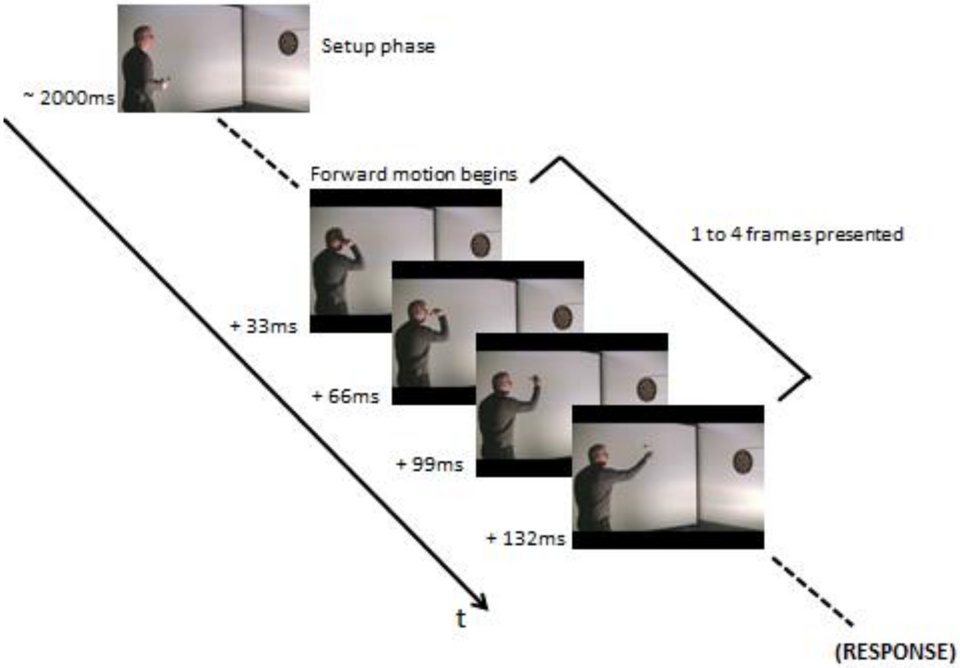


Figure 4

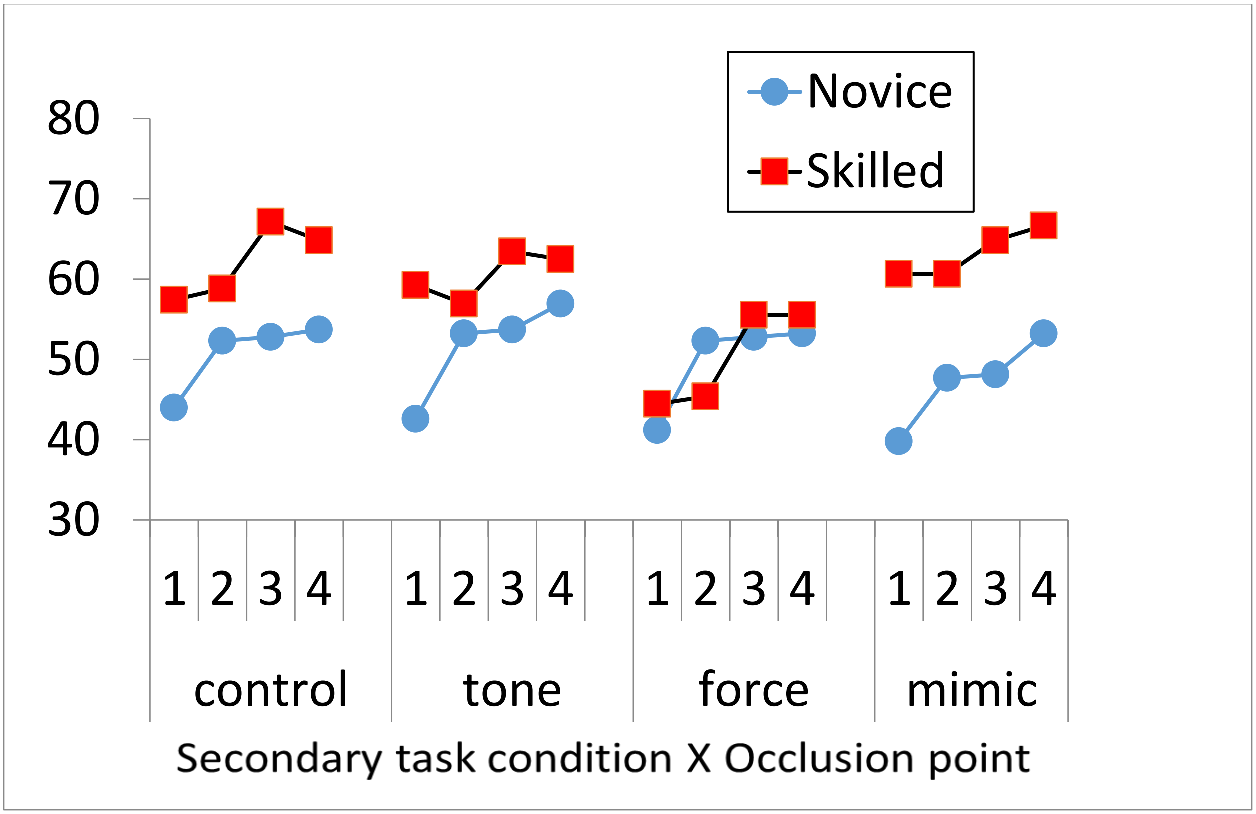

Novice
Skilled
80
70
60
50
40
30
1
2
3
4
control
tone
force
mimic
Secondary task condition X Occlusion point

Figure 5

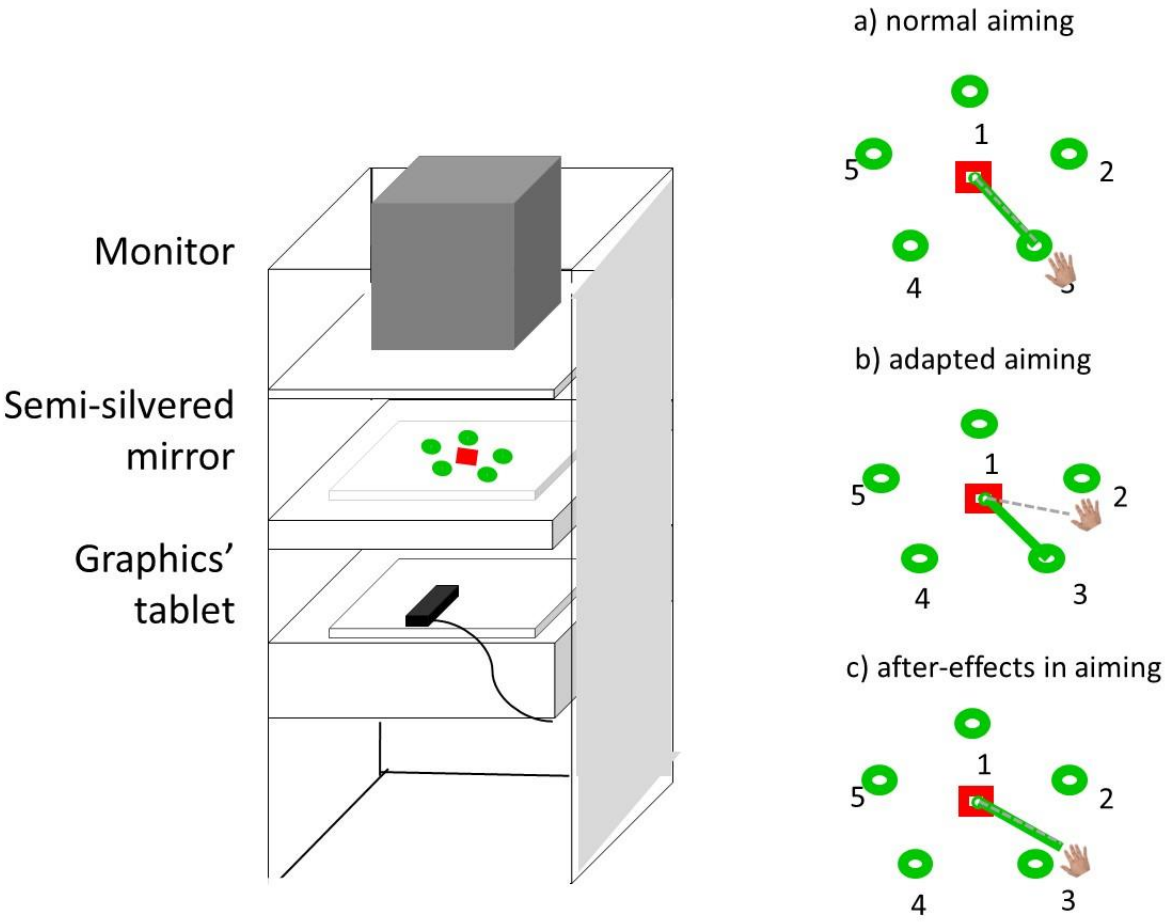
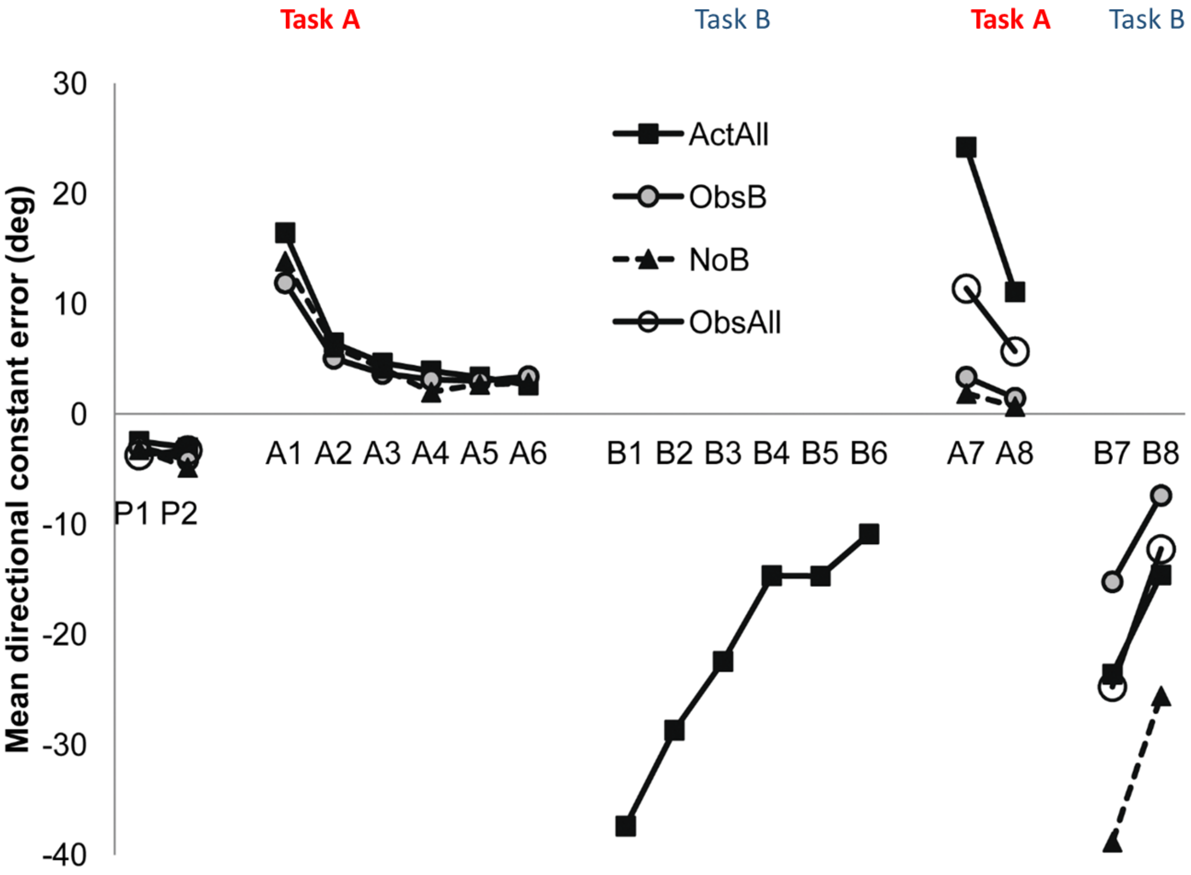

Monitor
Semi-silvered mirror
Graphics' tablet
a) normal aiming
1
2
3
4
5
b) adapted aiming
1
2
3
4
5
c) after-effects in aiming
1
2
3
4
5

Figure 6


Task A
Task B
Task A
Task B
Mean directional constant error (deg)
30
20
10
0
-10
-20
-30
-40
ActAll
ObsB
NoB
ObsAll
P1 P2
A1 A2 A3 A4 A5 A6
B1 B2 B3 B4 B5 B6
A7 A8
B7 B8