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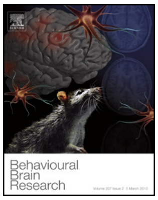

Research report

On the relationship between the execution, perception, and imagination of action

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HIGHLIGHTS

- It is thought that common coding systems enable action imagination and perception.
- Present work examined similarities in action execution, imagination, and perception.
- Consistencies in the speed-accuracy relationships in each task were observed.
- Amplitude of motor overflow during imagination scaled to imagined movement distance.
- Common coding account of action execution, imagination, and perception supported.

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ABSTRACT

Humans can perform, perceive, and imagine voluntary movement. Numerous investigations of these abilities have employed variants of goal-directed aiming tasks because the Fitts's law equation reliably captures the mathematical relationship between movement time (MT) and accuracy requirements. The emergence of Fitts's speed-accuracy relationship during movement execution, perception, and imagination has led to the suggestion that these processes rely on common neural codes. This common coding account is based on the notion that the neural codes used to generate an action are tightly bound to the codes that represent the perceptual consequences of that action. It is suggested that during action imagination and perception the bound codes are activated offline through an action simulation. The present study provided a comprehensive testing of this common coding hypothesis by examining the characteristics of the Fitts relationship in movement execution, perception, and imagination within the same individuals. Participants were required to imagine and perceive reciprocal aiming movements with varying accuracy requirements before and after actually executing the movements. Consistent with the common coding account, the Fitts relationship was observed in all conditions. Critically, the slopes of the regression lines across tasks were not different suggesting that the core of the speed-accuracy trade-off was consistent across conditions. In addition, it was found that incidental limb position variability scaled to the amplitude of imagined movements. This motor overflow suggests motor system activation during action imagination. Overall, the results support the hypothesis that action execution, perception, and imagination rely on a common coding system.

1. Introduction

Not only are we able to select, plan, and execute a variety of goal-directed actions, but we are also able to perceive and imagine these same movements. The nature of the potential commonalities between the processes underlying the execution, perception, and imagination of action has been considered for more than a century [1]. Also, there has been a fairly recent expansion of experimental attention to these issues [2,3]. The results of this recent work have revealed that there are similarities in the patterns of effects across tasks involving the execution, perception, and imagination of action. These similarities have led some researchers to conclude that all of these abilities rely on similar neural codes and networks.

More specifically, it has been suggested that the processes underlying action generation, perception, and imagination are enabled by an ideomotor (or common coding) network. In this common coding network, the neural codes that are responsible for generating a specific goal-directed action are tightly bound to the

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codes that represent the perceptual consequences of those actions (see Refs. [4,5] for reviews and more thorough discussions of this theory). It is thought that these codes are actively and fully engaged during the execution of action, but are run offline (i.e., at a sub-threshold level, which does not cause the actual movements to emerge) during action perception and imagination [2,6]. Although there are separate lines of research investigating the similarities in action execution and perception [2] and action execution and imagination [3], there has yet to be a systematic study of all these tasks in the same group of individuals. The purpose of the present study was to address this limitation and, thereby, provide a comprehensive testing of the common coding account of action execution, perception, and imagination.

1.1. Ideomotor coding

The common coding account of action execution, perception, and imagination is based on the tenet that the motor representation of an action is tightly bound to the representation of the perceptual consequences (effects) of that action [4,5]. The binding of action and effect codes only occurs via training and/or experience in which the individual repeatedly perceives a specific stimulus following the execution of a specific action. An important consequence of this experienced-based binding for the individual is that the activation of one code automatically activates the companion bound code [7,8]. In the context of action execution, this series of coupled activations is thought to facilitate efficient and accurate response selection. The logic behind this hypothesis is derived from the idea that conceiving of a desired effect will drive the activation of the appropriate response to bring about that effect and, likewise, formulating a specific action can activate the codes of the effect of that action to allow the individual to predict the consequences of the selected action [4]. For example, the desire to make your avatar in a video game jump will activate the action plan to press a specific button on the game controller, and the action plan to press a specific button on game controller can be used to predict that that action will cause the avatar to jump. Notably, it is only through the experience of pressing different buttons on the controller in that specific gaming environment that the individual will know and accurately characterize the specific action requirements (e.g., which button to push or joystick to manipulate) and the specific action the avatar will execute.

Researchers that have advanced the common coding account of action perception and imagination suggest that these two tasks are completed by running the common codes offline. In the case of action perception, it is thought that the observation of an action activates the perceptual representations that code for the observed motion pattern and/or the perceptual consequences of the actions. The activation of the perceptual codes subsequently leads to the excitation of the bound motor codes that would bring about the observed actions and consequences. The active effect and motor codes are then accessed by other systems to allow for a wide variety of tasks including action perception [2,6,9] and the planning of joint action [10–12]. One of the main lines of evidence that supports the hypothesized active engagement of the motor system during action perception is the repeated observation of changes in activity in primary motor cortex when people observe someone else performing an action [13–19]. Importantly, these changes in the activation of the motor system are sub-threshold and do not elicit overt movement execution.

In the case of action imagination, it has been proposed that the action/effect codes are endogenously excited and operated offline to allow the individual to experience task execution at a sub-threshold level. Consistent with the literature on action perception, the finding of sub-threshold changes in the activation of the motor system during action imagination [15,20,21] (see Ref. [22] for a review) support this common coding hypothesis. In addition to this neurophysiological evidence supporting the notion that the motor system is active during imagination and perception, there is also evidence for the hypothesis that common coding systems underlie these processes that has been derived from behavioural studies that explore the speed/accuracy trade-off that occurs during goal-directed action. These studies form the basis of the present work and will be reviewed next.

1.2. Fitts's law in execution, perception, and imagination

In a series of recent behavioural studies, researchers have exploited the well-characterized speed-accuracy trade-off that occurs when actors are attempting to execute movements of different difficulties as quickly and as accurately as possible. The essential trade-off that occurs is that actors increase movement time (MT) in an attempt to maintain comparable levels of precision across movements with increasing difficulty. This relationship between movement difficulty and movement time is captured in Fitts's law equation [23]. The formal equation is:

$$\mathrm{MT} = a + b\left(\log_2 \frac{2A}{W}\right)$$

where a and b are constants that relate the individual's base MT (y-intercept) and the increase in MT as a function of movement difficulty (the slope of the regression line). The ($\log_2 [2A/W]$) component of the equation quantifies the difficulty of the movement in bits of information. This index of difficulty (ID) is a function of the width of the target (W) and the movement amplitude (A). Effectively, ID increases as the width of the target (W) decreases and/or the movement amplitude (A) increases. Because the relationship between MT, accuracy, and specific target variables has been quantified and established, Fitts's law tasks provide an excellent control platform to develop specific predictions regarding movement execution, perception, and imagination.

One of the first studies to investigate motor imagery using the relationship between movement time and movement difficulty was conducted by Decety and Jeannerod [24]. Participants in this study were asked to imagine themselves walking through different doorways as quickly as possible and to report the time it took to walk through the door. The starting distance from the door and the width of the door was manipulated in a manner consistent with Fitts's law. The critical finding of the study was that the times reported to walk through the different doorways (i.e., the imagined walking MT) increased when the doorways were narrower and the distance to the door increased—a pattern of MTs consistent with Fitts's law. In more recent and directly relevant research, Young et al. [3] and Sirgiu et al. [25] showed that the Fitts's law relationship existed in both executed and imagined movements in a discrete goal-directed movement task. Interestingly, their data revealed that imagined MTs were longer than actual MTs. Thus, although the speed-accuracy trade-off was present in imagined movements, participants over-estimated the time in the imagined task suggesting that the offline simulation is slightly detuned or runs more slowly than the actual movements are executed.

The processes underlying action perception have been studied in a parallel, but separate, series of studies using a Fitts's law task. In a study by Grosjean et al. [6], participants watched videos of a person completing a continuous series of aiming movements with their index finger between two targets at different speeds (i.e., reciprocal aiming movements). The task of the participant was to determine if they thought it was possible or not to maintain the accurate termination of the movement on the targets while moving between the two targets at the observed speed in a given video. The videos actually consisted of two pictures (one with the finger of the model on the right target and one with the finger of the model on the left