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Information about relative phase in bimanual coordination is modality specific (not amodal), but kinesthesis and vision can teach one another

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ABSTRACT

How is information from different sensory modalities coordinated when learning an action? We tested two hypotheses. The first is that the information is amodal. The second is that the information is modality specific and one modality is used in first learning the action and then is used to teach the other modality. We investigated these hypotheses using a rhythmic coordination task. One group of participants learned to perform bimanual coordination at a relative phase of 90° using kinesthesis. A second group used vision to learn unimanual 90° coordination. After training, performance using the alternate modality was tested in each case. Snapp-Childs, Wilson, and Bingham (2015) had found transfer of 50% of learned performance of 90° coordination between the unimanual and bimanual tasks when each had included use of vision. Now, we found essentially no transfer (≈5%) indicating that the information was modality specific. Next, post-training trials performed using the untrained modality were alternated with trials in which kinesthesis and vision were used. The result was that performance using the untrained modality progressively improved. We concluded that trained modality was used to teach the untrained modality and that this likely represents the way information from different sensory modalities is coordinated in performance of actions.

1. Introduction

One of the classic questions in the study of perception is how different perceptual modalities, like kinesthesis and vision, coordinate and interact. Recent sensory integration models have borrowed from cue combination models in visual space perception where different cues about distance, for instance, are described as first interpreted as estimates of distance and only then combined, usually in a weighted average (e.g. Landy, Maloney, Johnston, & Young, 1995). In sensory integration, kinesthetic and visual information about limb position have also been modeled as combined via weighted averages of position estimates (van Beers, Sittig, & Denier van der Gon, 1996, 1999). An alternative approach to such 'weak fusion' models is to combine information as such, that is, before it is interpreted (Domini, Caudek, & Tassinari, 2006; Tassinari, Domini, & Caudek, 2008). If this approach is applied to sensory integration and if different sensory modalities each yield measurements of the same information, they would nevertheless entail different modality specific measurement noise. An advantage of the approach would be that the measurement noise can be reduced when the information is combined and then, interpreted.

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This latter approach was inspired, in part, by Gibson's (1950, 1966, 1979) suggestion that information about an event that is detected simultaneously via different modalities might itself be amodal, that is, the same in different modalities. (See Epstein (1985) for a review of Gibson's ideas about amodal information.) A well-known example of this is the frequency of bouncing used as information in visual and auditory perception of bouncing events, for example, bouncing balls (Warren, Kim, & Husney, 1987) or bouncing glass bottles or broken fragments thereof (Warren & Verbrugge, 1984). A related example would be the perception of tapping in coordinated rhythmic limb movements (Repp, 2005).

Rhythmic bimanual coordination has been studied extensively and shown to entail use of kinesthetic and/or visual information to establish and maintain a given coordination (e.g. Ren et al., 2015; Swinnen, Jardin, Meulenbroek, Dounskaia, & Hofkens-Van Den Braindt, 1997; Temprado, Swinnen, Carson, Tourment, & Laurent, 2003). Accordingly, the question of combination and interaction of information from different sensory modalities arises in this context. The original phenomena in the study of coordination were established in studies performed by Kelso (1984). One of the phenomena was the spontaneous switching between coordinative modes with increase in the frequency of rhythmic movement from slower preferred rates to rates that are 2–3 times faster. Participants starting in an anti-phase (or 180°) mode become increasingly unstable in respect to the coordination as the frequency increases and spontaneously switch to an in phase (or 0°) mode. Haken, Kelso and Bunz (1985) developed a nonlinear dynamical model, called the 'HKB model', that represented this phenomenon in terms of a potential function with wells or attractors at 0° and 180°. The well at 180° was gradually eliminated with increase in frequency of oscillation.

Subsequently, the potential function in the HKB model was hypothesized to originate from perceptual coupling of the rhythmic movements (Bingham, 1995). The form of the potential function was produced by results of visual judgment studies in which observers judged the stability of relative phase in a series of different rhythmic coordinations, that is, relative phases of 0°, 45°, 90°, 135°, and 180° (Bingham, Schmidt & Zaal, 1999; Bingham, Zaal, Shull, & Collins, 2001; Zaal, Bingham, & Schmidt, 2000). Change in the form of the function (loss of the well at 180°) was also produced with increases in movement frequency (Bingham, 2003, 2004; Bingham et al., 2001). Thus, the function was perceptual, or visual, but then Wilson, Craig and Bingham (2003) performed a kinesthetic judgment study using the same movements and coordinations as had been used in the previous study. Blindfolded participants judged the stability of relative phase as they actively tracked two manipulanda that produced the various rhythmic movements. The results were nearly identical to those of the visual judgment studies. These results led to the suggestion that the information for relative phase in the two modalities, vision and kinesthesis, might be amodal.

A nonlinear dynamical model was formulated that included terms representing perceptual information about relative phase (Bingham, 2003, 2004; Snapp-Childs, Wilson, & Bingham, 2011). The information was the relative direction of movement and its detection was conditioned by the relative speeds of movement. This information could indeed be the same in the visual and kinesthetic modalities. Given uni-dimensional limb movement, either vision or kinesthesis could yield specification of the direction along the dimension of movement (e.g. leftward or rightward in vision and flexion or extension in kinesthesis). Results of perturbation studies have provided support for the hypothesis that relative direction of movement specifies relative phase (Wilson, Collins, & Bingham, 2005; Wilson & Bingham, 2008). Quite a number of studies have now demonstrated the role of perception in the coupling of movements performed in rhythmic coordination tasks (e.g. Kovacs, Buchanan, & Shea, 2009; Mechsner, Kerzel, Knoblich, & Prinz, 2001; Schmidt, Carello, & Turvey, 1990; Serrien, Li, Steyvers, Debaere, & Swinnen, 2001; Temprado & Swinnen, 2005; Temprado et al., 2003; Wilson & Bingham, 2005; Wilson et al., 2005; Wimmers, Beek, & van Wieringen, 1992).

Participants have been shown to be able to learn to perform new rhythmic coordinations (e.g. 90° relative phase) stably when the performance before learning had been unstable and would transition away to stable modes, namely, 0° or 180°. Using a visual coordination task, Wilson, Snapp-Childs, and Bingham (2010) showed that strictly perceptual learning yielded the ability to perform a new coordination. Participants acquired the ability to visually discriminate a 90° coordination with good resolution. Once they were able to do this, they were also able to produce the coordination without having practiced the limb movements. Kovacs et al. (2009) tested participants' ability to produce 90° coordination without extensive training, but using transformed information that made the coordination easy to recognize and discriminate. Lissajou displays are position-position plots in which 0° coordination appears as a diagonal line of positive slope, 180° coordination appears as a diagonal line of negative slope, and 90° coordination appears as a circle. Using this information, participants were found to be able to produce 90° readily and without significant practice. However, participants were dependent on the special visual information. When it was removed, the coordination could no longer be produced. Subsequent studies showed that participants could be weaned off the Lissajou display using a faded information protocol in which the Lissajou display was only intermittently available during practice. One way to interpret this result is that vision was being used to train kinesthesis. The kinesthetic information specifying a 90° coordination would only be available when the coordination was being successfully performed. The transformed visual information allowed the coordination to be performed and while it was performed, if participants split their attention between the visual information used to produce and control the limb movements successfully and the kinesthetic information that was made available in the process, they could become sensitive to the new kinesthetic pattern, that is, do perceptual learning. This is one way that different sensory modalities might interact in perception and action. There was little question in this instance that the information in the two modalities, vision and kinesthesis, was different, that is, not amodal, but modality specific.

Mechsner, Kerzel, Knoblich and Prinz (2001) found that if a performer was acting to produce and maintain a visually perceived 0° coordination while moving his or her limbs in an anti-phase or 180° coordination defined in terms of non-homologous muscle groups, then the movements would exhibit the stability of 0° coordination and remain stable despite increases in the frequency of movement. Mechsner et al. suggested that the coordinative modes are determined in a spatial frame of reference rather than a muscular frame of reference. Furthermore, Mechsner et al. reported that they had replicated this result when vision of the limb movements was prevented requiring the movements to be guided using kinesthesis. This implies that the information used to perceive the coordination,