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The development and learning of the visual control of movement: An ecological perspective

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Abstract

We compare development and learning of the visual control of movement from an ecological perspective. It is argued that although the constraints that are imposed upon development and learning are vastly different, both are best characterised as a change towards the use of more useful and specifying optic variables. Implicit learning, in which awareness is drawn away from movement execution, is most appropriate to accomplish this change in optic variable use, although its contribution in development is more contentious. Alternatively, learning can also be affected by explicit processes. We propose that explicit learning would typically invoke vision for perception processes instead of the designated vision for action processes. It is for that reason that after explicit learning performance is more easily compromised in the face of pressure or disorders. We present a way to deal with the issue of explicit learning during infancy. © 2003 Elsevier Inc. All rights reserved.

Keywords: Perceptual-motor development; Explicit learning; Implicit learning; Dorsal and ventral stream; Information

1. Introduction

Perhaps the most powerful portrayal of development is Shirley's black silhouetted infants laid down in a chronological series of motor milestones. It readily conveys the message that development normally proceeds with great regularity and inevitability. We can outline the age and

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sequences of these motor milestones, and much other behaviour, quite reliable. This portrayal lent itself to prescriptive theories of development that sought the source of developmental order within the organism (see Pick, 2003). Today these neuro-maturational perspectives are rightly rejected, and alternative theories have been proposed -most notably the dynamic systems perspective advocated by Thelen and Smith (1994). In short, developmental change is thought to emerge from context-dependent dynamic interactions of multiple factors. Not a single cause, either genetic or environmental, but all factors and context determine developmental change. Although the benefits of the dynamical systems perspective for the understanding of developmental change are without question, the emphasis on the process of change might obscure the factor age as an essential characteristic of development. For example, Thelen and Smith (1994, p. xviii) list several goals which they believe to be essential for a theory of development, the most important of which is an understanding where novel behaviour comes from. However, the issue of the origin of novelty, like any of the other listed goals, is not restricted to the domain of development, but is also dealt with in theories of learning. Rather than a theory of developmental change the dynamic systems perspective may be defined more appropriately as a general theory of change. It remains silent with respect to one of the core messages conveyed by Shirley's black silhouetted infants; that we can outline the age of the motor milestones quite reliable. It is this apparent omission of the age variable that leads us to fall back on the work of Wohlwill.

Wohlwill (1970, 1973) contended that the changes with age constitute an inherent characteristic of development. He further argued that age should be conceptualised as part and parcel of the dependent variable in developmental studies. To illustrate his claim, he refers to the variable time in studies of adult perceptual adaptation. Like development, perceptual adaptation is thought to involve systematic changes in behaviour over time. In studies of dark adaptation changes in threshold over time are charted without attributing any causal significance to the time variable itself. Independent variables are introduced to show the role of factors such as wavelength or the size of the retinal field on the rate of adaptation. This demonstrates how different parameters influence the *course* of adaptation. These changes in the dark-adaptation curve constitute an inherent characteristic of the perceptual system, and may be explained in terms of physiological processes. Changes over time, however, remain essential to the description of the adaptation process. Hence, researchers in perceptual adaptation do not aim to manipulate variables for which time could be considered to represent a mere shorthand (see Wohlwill, 1970, p. 53; 1973, p. 23).

According to Wohlwill, the place of time in perceptual adaptation studies, or the number of trials in studies of learning, is similar to the place of age in developmental studies. Therewith the task for developmental studies becomes first of all one of describing the form or mode of the relationship between age and the changes observed to occur in some behavioural variable over the course of development. Only those behavioural variables qualify as developmental for which changes with age (in terms of direction, sequence, shape, etc.) remain invariant over a broad range of particular environmental conditions or circumstances, as well as genetic characteristics (Wohlwill, 1970, p. 52). In this respect, Wohlwill points to the development of speech, space perception and also to motor development -the topic of the present paper. Thus, as far as changes in, for instance, prehension and locomotion occur in a vast majority of infants in the most diverse environments and under the most varied conditions of experience in

most cultural groups and typically within a fairly narrowly delimited age period, they can be considered as true developmental phenomena. In contrast, changes over time (or even with age) observed only for individuals subjected to specific experiences, such as skills acquired through directed teaching in racquet sport, would qualify as learning and not as development. Wohlwill (1970) emphasised that his distinction is not similar to the one McGraw introduced between phylogenetic and ontogenetic behaviours. Developmental variables are not to be conceived as independent of environmental influences. What is meant is that the occurrence of change with age is independent of specific environmental conditions; it cannot be produced by experimental manipulation. To be sure, Wohlwill adds that an investigator should not be content with merely observing developmental change. The limitations of experimental manipulation of particular variables, however, should also be recognised; it can only affect the *course* of such change (e.g., the rate of development).

Wohlwill's conceptualisation forms the working assumption in our inquiry into the changes over time in how vision guides action during development (e.g., eye blinking, grasping, etc.) and learning (e.g., returning a tennis serve). Our aim is to provide a description of these changes from the ecological perspective (Gibson, 1979), in which for the greater part we shall restrict ourselves to changes governing the visual control of movement. We specifically ask whether the form of the relationship between age and the changes that occur in the visual control of movement during development is similar to the relationship between amount of practice and the changes that occur in the visual control of movement during learning. To this end, we describe how the visual control of movement is organised (i.e., vision for action and vision for perception), and how the changes over time in the visual control of movement during development and learning can be characterised (i.e., the education of attention). We then explore how attention-specific processes (i.e., implicit and explicit learning) can differentially facilitate these changes during learning. We end by speculating whether similar attention-specific processes might also influence the course, as opposed to the occurrence (!), of the development of the visual control of movement during infancy.

2. The organisation of the visual control of movement

2.1. *Vision for action and vision for perception*

Recently proponents of the ecological perspective have endorsed the view that our visual system can be classified into two subsystems with different functions (e.g., Michaels, 2000; Pagano & Bingham, 1998; Van der Kamp, Savelsbergh, & Rosengren, 2001; see Fig. 1). On the one hand, a dorsal stream can be discerned that uses visual information to control goal-directed movements, that is, to tune these movements to the requirements of the environment (i.e., vision for action). On the other hand, a ventral stream can be distinguished that encompasses the use of visual information to obtain knowledge of the environment and the self (i.e., vision for perception). This separation between vision for action and vision for perception has been adopted from recent ideas, most notably those of Milner and Goodale (1995; see also Bridgeman, Kirch, & Sperling, 1981; Jeannerod, 1997). However, the original ideas clearly depart from the ecological perspective in the sense that they bear an unmistakably computational and repre-

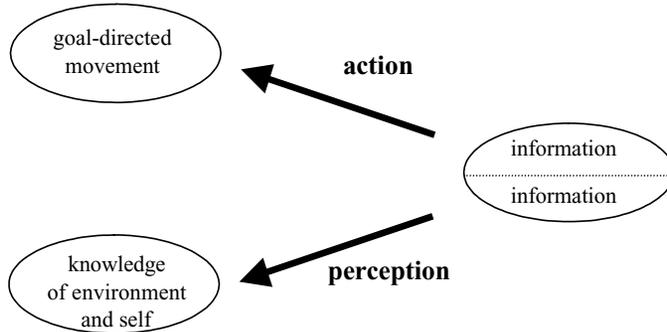


Fig. 1. A schematic representation of the separation between vision for action and vision for perception. The dotted line in the “information box” illustrates that distinct sources of visual information may be involved in action and perception.

sentational flavour. A distinction based upon the way visual cues are transformed and encoded by the brain would not be acceptable to proponents of the ecological perspective. Therefore, the ecological perspective proposes an information-based distinction between vision for action and vision for perception in terms of the type of the visual information sources that is used and the manner in which the sources of information are used (Van der Kamp & Savelsbergh, 2000).

Table 1 summarises the most salient information-based differences between vision for action and vision for perception (extensive reviews can be found in Creem & Proffitt, 2001; Goodale & Humphrey, 1998; Michaels, 2000; Norman, 2002; Rossetti, 1998; Rossetti & Pisella, 2002; Van der Kamp & Savelsbergh, 2000). Here it suffices to say that the visual control of goal-directed movements (i.e., vision for action) is a process that primarily but not exclusively involves egocentric sources of information, is fast, short-lived and implicit. For example, in prehension grasping movements are mainly based upon information that specifies size and distance of an object in relation to the aperture of the hand. The use of information to guide hand aperture is, and must be, an almost instantaneous (“on-line”) process about which one is not aware, otherwise performance would be disturbed. Instead, obtaining knowledge of the environment or the self (i.e., vision for perception) is considered to be a slow, long-lived, and

Table 1
Information-based differences in vision for action and vision for perception

Information	Vision for action	Vision for perception	Study
Sources	Egocentric Monocular dynamic and binocular Peripheral and central field of view	Allocentric Monocular static (pictorial) Central field of view	Bridgeman et al. (1981) Marotta, Behrmann, and Goodale (1997) Goodale and Murphy (1996)
Control features	Fast (on-line), short-lived Implicit, unaware Control	Slow, long-lived Explicit, aware Perception of affordances	Bridgeman et al. (1997) Rossetti (1998) Passingham and Toni (2001)

mostly explicit process that primarily but not exclusively involves allocentric sources of visual information. Thus the perception of object characteristics is much more reliant on information that specifies, for instance, the size of an object in relation to the sizes of surrounding objects. The perceiver is aware of what she or he sees (e.g., it can be verbalised), even long after the event has been presented. In addition, several authors (e.g., Goodale, 1998; Goodale & Humphrey, 1998; Passingham & Toni, 2001) have stressed that the knowledge obtained through vision for perception also enables actors to identify the goal for action or to decide about the appropriate action. That is, vision for perception encompasses the perception of what the situation affords for action (see Postma, Van der Lubbe, & Zuidhoek, 2002; Van der Kamp et al., 2001). However, it is the vision for action system that controls the execution of actions.

2.2. An alternative route of movement control

Although most attention has been focussed on the dissociation, it is clear that both visual systems are closely intertwined in the course of action (Rossetti & Pisella, 2002). That is, apart from the specialised vision for action system, which is fast and implicit, goal-directed movements can be controlled by the vision for perception system as well. However, the visual control of movement is thought to be organised through this alternative route only under specific conditions. An imposed time delay between the detection of information and the initiation of the movement is one of these circumstances. For instance, Gentilucci, Chieffi, Daprati, Saetti, and Toni (1996) required healthy participants to point from one to the other arrow end of two types of the Müller–Lyer illusion (i.e., with arrows directed to or away from the centre of the line). The effect of the illusion on pointing was very weak under full vision. However, the pointing distance was increased or shortened according to the type of illusion when the movement was started after an imposed delay between the presentation of the visual illusion and the execution of the pointing movement. This finding suggests that delayed actions induce movement control based on allocentric sources of information (i.e., the arrow ends are taken into account) and thus organised via the slow and explicit vision for perception system (see also Bridgeman, Peery, & Anand, 1997; Carrozzo, Stratta, McIntyre, & Lacquaniti, 2002; Westwood, McEachern, & Roy, 2001).

A second condition in which the vision for perception system may be involved in movement control is when the execution of movement is accompanied by an explicit verbalisation. Rossetti (1998) reports a study where participants were presented an array of visual targets. The participants had to point to the target that changed colour as soon as the targets disappeared from screen (i.e., pointing without vision after zero time delay). In one of the conditions, participants were required to speak aloud the number associated with the pointed target during each movement. In contrast to the errors of the pointing movements without verbalisation, which were aligned with the movement direction, the pointing errors in this specific target verbalisation condition (but not in other non-sense verbalisation conditions) were aligned with the surrounding target array (see also Carrozzo et al., 2002; Gentilucci, Benuzzi, Bertolani, Daprati, & Gangitano, 2000). This suggests that verbalisation during movement execution induced movement control based on allocentric sources of information and thus organised through the vision for perception system.

In sum, both a specialised and an alternative route to the visual control of goal-directed movement can be distinguished. Normally, it is the vision for action system that is designated to control movement. However, it is likely that both time delays and explicit verbalisations perturb or even suppress the specialised vision for action system, and enforce the involvement of the route through the vision for perception system (Rossetti, 1998). In this case, however, the control of goal-directed movement has changed into a slow and explicit step-by-step process that primarily uses allocentric sources of visual information.

2.3. A note on the development of the vision for action and vision for perception systems

Before we turn to the types of change that underlie the development and learning of the visual control of goal-directed movements, we briefly discuss arguments concerning the origin and development of the dissociated vision for action and vision for perception systems. Several authors have recently reasoned that vision for action and vision for perception follow different developmental trajectories from birth. Hence, in contrast to most traditional theories of development (e.g., Piaget, 1952), neither vision for action nor vision for perception is considered as privileged in development. The two are thought to develop independently (Bertenthal, 1996; Van der Kamp & Savelsbergh, 2000, 2002) and at different rates (Atkinson, 2000; Kovács, 2000; Newman, Atkinson, & Braddick, 2001). In addition, it is hypothesised that ego- and allocentric sources of information contribute differently to the developmental changes within vision for action and vision for perception (Kaufman, Mareschal, & Johnson, 2003; Van der Kamp & Savelsbergh, 2000). For instance, Wattam-Bell (1996 in Atkinson, 2000) found that the perception of direction of motion after 10 weeks of age is exclusively based on relative motion, that is, the direction of a target in relation to its background (i.e., allocentric information). It was only several weeks later that infants were able to distinguish different directions of motion on basis of absolute direction of motion of the target without a background (i.e., egocentric information). In contrast, Von Hofsten, who found that even newborns direct their arm to a moving object, concludes that within the early development of reaching "... the infant reaches in reference to a coordinate system fixed to the moving object instead of to a static background" (Von Hofsten, 1983, p. 84). Observations like these show the potential of obtaining insight in the issue of dissociation during development between vision for action and vision for perception by examining the differential roles of ego- and allocentric sources of information.

However, plausible these arguments might seem, it is important to bear in mind that the hypothesis of vision for action and vision for perception following different developmental trajectories has not been directly tested in infants. The evidence so far mainly stems from age-based comparisons of the findings from various studies. There are a few studies that examined the effects of visual illusions on the control of arm movements in young children between 5 and 12 years of age (Gentilucci, Benuzzi, Bertolani, & Gangitano, 2001; Hanisch, Konczak, & Dohle, 2001). The findings are difficult to interpret, but they do seem to suggest that visual illusions may affect arm movements to a greater extent in children than in adults. This might suggest that the relative contribution of allocentric sources of information, and hence the vision for perception system, during the visual control of movement is somewhat larger in young children than in adults.

3. The ecological perspective to development and learning

3.1. *The state of the ecological perspective*

Almost 10 years ago, Michaels and Beek (1995) made the following provocative characterisation about the state of the ecological perspective with respect to development and learning: “Unfortunately, empirical work on learning within the direct perception school appears limited to demonstrating that learning occurs (or does not have to occur, as in the case of new-borns and looming), and theory is little more than a collection of slogans and metaphors” (p. 273). This collection of slogans and metaphors, according to Michaels and Beek, consists of not more than the portrayal of learning as the education of attention (Gibson, 1966) or as perceptual differentiation (Gibson, 1966; Gibson & Gibson, 1955). This may be regarded as a harsh statement, certainly given the large body of literature on the development of the perception of affordances (e.g., Gibson, 1969, 1988; see also Eppler & Adolph, 1996). Nevertheless, the theoretical basis for studying development and learning at the time could perhaps be considered as a little shallow. Several investigators have suited the action by the word and proposed a broader ecological theory of development and learning (Jacobs & Michaels, 2002; Jacobs, 2001; Runeson, Juslin, & Olsson, 2000; see also Van Hof, Van der Kamp, & Savelsbergh, 2004).

In the present section, we aim to describe the form of change over time in the visual control of movement during development and learning. The ecological perspective holds that there is a lawful relation between visual information and movement (Warren, 1988; see also Jacobs, 2001). In its simplest appearance, the so-called law of control for a certain action can be formally expressed as

$$M(t) = a + b \times I(t),$$

where $M(t)$ stands for a particular movement variable, $I(t)$ stands for a particular optic variable, and a and b stand for tuning constants. The law of control describes the action as the on-line coupling between optic and movement variables. Lee, Young, Reddish, Lough, and Clayton (1983) provide a well-known example of such a control law for the visual control of timing the leap to punch a falling ball. They show that change in knee angle (i.e., $\alpha(t)$) is a function of the optical variable tau (i.e., $\tau(t)$), which specifies current distance of the falling ball divided by approach velocity. The constants are thought to represent adaptive adjustments in linking the visual information to the leg movement. If we assume that goal-directed movements are indeed lawfully controlled by visual information than three types of changes can be discerned that underlie its development and learning: the discovery of a law of control, the education of attention, and calibration. The first comprises the establishment of an appropriate law of control, the second refers to a change of the optic variable that enters a particular control law, and the last concerns an adaptive change in the relation between the movement and optic variables. Below, we summarise the current evidence for these types of change over the course of development and learning. We will conclude that a change towards the use of a more useful and specifying optic variable is the most appropriate description of the form of change over time of the visual control of movement.

3.2. *Types of change*

3.2.1. *The discovery of the law of control*

A manifold of actions may be possible in an environment, but infants or beginner learners still have to discover what the environment affords for action. An intricate element of this process is the establishment or formation of a law of control. That is, finding an appropriate action cannot be comprehended apart from discovering an appropriate coupling between information and movement. There is a dearth of studies, however, that explicitly focus on the set-up of action (i.e., the formation of the control law). The majority of ecologically based developmental studies, for instance, appear to be concerned mainly with the process of discovering affordances for locomotion (e.g., Adolph, 1997; Gibson et al., 1987; Gibson & Walk, 1960) or prehension (e.g., Needham, Barrett, & Peterman, 2002; Yonas & Hartman, 1993). These studies demonstrate the active nature of the infants' search of what the environment affords, or put it differently, what actions are appropriate to actualise. For example, infants look around, touch and feel sometimes with both the hands and feet, shift posture and so on to explore whether a ground, cliff or slope is crossable. It is convincingly shown that exploration for action is not a blind random search; it is specific for the to-be-perceived environmental properties (e.g., Gibson et al., 1987) and specific for each action or posture (e.g., Adolph, 2000; Gibson et al., 1987). If we assume that this exploratory behaviour of the infants encompasses the search for and the formation of a lawful relation between movement and information, then these studies would suggest that the discovery of an appropriate law of control is information based (cf. Jacobs, 2001).

In the area of learning, the evidence for the process of the discovery of the law of control is even more circumstantial. Nevertheless, studies that examine novice-expert differences in visual search patterns during interceptive actions might shed some light on the issue. In racquet sport, for instance, performers face severe spatial and temporal task constraints. Hence, players preparing to receive a ball or shuttle must begin initiating their movements very early, mostly before the opponent has completed his stroke. A novice first has to make sense of what actions can be actualised, that is, how to set-up an appropriate coupling between movement and information. Carrough and Janelle (2002) report that the visual search patterns of novices and experts when presented with various dynamic presentations of serves and ground strokes were markedly different. The visual search patterns of the novices were scattered in highly variable manner to various locations, irrespective of the opponent's stroke and rather inconsistent from presentation to presentation. It appears then that the beginner player is in the process of discovering the affordances; he is visually exploring the situation to find out what actions are appropriate.¹ The experts, in contrast, already knew the affordances of the situation. They exhibited stroke-specific visual search patterns clustered around specific locations that were highly consistent across multiple presentations (Carrough & Janelle, 2002; see also Savelsbergh, Van der Kamp, Oudejans, & Scott, 2004).

3.2.2. *The education of attention*

The same action may be actualised by coupling different optic variables to the same movement variable. Hence, a change over time in development and learning may be described as a change in the optic variable that is incorporated in the law of control. This is where Gibson

(1966) introduced the process of education of attention, which is described as “a greater *noticing* of the critical differences with less noticing of irrelevancies” and “a progressive focusing or centering of the perceptual system” (Gibson, 1966, p. 52), or as an “optimization of attention” (Gibson, 1969, pp. 456–462). Jacobs and Michaels (2002) argue that this “optimization of attention” entails a change from detecting non-specifying to specifying² variables (see also Oudejans, Bleijendaal, Koedijker, & Bakker, 2003). Only when a perceiver detects a variable that *specifies* the property that she or he intends to perceive, attention is appropriately educated. Eleanor Gibson has often (e.g., Gibson, 1969; Gibson & Pick, 2001) pointed at this process as one of selection or differentiation, where the perceiver is “narrowing down from a vast manifold of information to the minimal, optimal information that specifies the affordance of an event, object or layout” (Gibson & Pick, 2001, pp. 150–151).

Recently, Kaye and Van der Meer (2000) have made observations that hint to the education of attention as a process that underlies changes in the control of defensive blinking to optical collisions during infancy. In a cross-sectional study, these authors found that 6–7-month-old infants blinked when the relative rate of expansion of the optical pattern (i.e., tau) generated on a shadow-caster reached a critical value. The detection of this variable allowed the infants to blink in time under different constant velocity and constant accelerative approaches of the virtual object. Hence, these infants appeared to have appropriately directed their attention to the specifying variable. The 5–6-month-old infants, in contrast, did not cope successfully with all the virtual object’s approaches, the fastest accelerative approach resulted in late blinking. It was shown that this was due to the younger infants’ using a threshold optical angle, a non-specifying variable that leads to less appropriate blinks. A similar change towards the use of more useful optic variables around 6 months has recently been observed for the development of catching moving objects (Van Hof & Van der Kamp, 2003; see also Van der Meer, Van der Weel, & Lee, 1994).

Examples of expertise differences that indicate changes in optical variable use in the visual control of movement are also available from the motor learning literature (see Carraugh & Janelle, 2002; Williams, Davids, & Williams, 1999). Occlusion paradigms in racquet sports, in which either the temporal or spatial characteristics of an event (e.g., an opponent’s service) are selectively obstructed from view, indicate that experts use sources of information that occur earlier in the proximal-to-distal unfolding action of the opponent than do novices and intermediates. More specifically, several studies suggest that novices primarily rely on sources of information related to early ball flight and racquet displacement, whereas experts also used information generated by—in particular—movement of the playing arm and the trunk rotation to get at the right place at the right time (e.g., Abernethy, 1990; Abernethy & Russell, 1987). It is this difference in the attended optic variables that appears to account for the skill-related variability in performance. In sum, the education of attention seems an important process underlying both the development and learning of the visual control of movement. However, the evidence would even be more convincing if there was not such a paucity of longitudinal studies. Ultimately, a longitudinal methodology, and not the present age- and skill-based comparisons, is needed to chart change with age or change with practice (Thelen & Smith, 1994; Wohlwill, 1973).

3.2.3. Calibration

The third process underlying improvements in the visual control of movement that can be distinguished is calibration. Calibration is the process of tuning and maintaining the specific

relation between the attended optic variable and the unfolding movement (Jacobs, 2001; Jacobs & Michaels, 2002). The study of Jacobs (2001) in which participants learned to catch a ball that approached from different angles may serve as an example. Improvements in performance were found to go hand in hand with catchers adjusting the threshold of the involved optic variables, which can be represented by a change in tuning constant b in the law of control. Only occasionally were improvements in performance based upon a change in optical variable on which the control of the movement was based (i.e., education of attention). Unfortunately, we found no other studies assessing the process of calibration in relation to developmental or learning changes of the visually control of movement—although there is a wealth of evidence about calibration from adaptation studies (e.g., Van der Kamp, Bennett, Savelsbergh, & Davids, 1999; Withagen & Michaels, 2002).

3.3. Commonalities in the form of change during development and learning

The ecological perspective describes three types of changes that underlie development and learning of the visual control of goal-directed movements. First, an appropriate coupling between movement and information needs to be discovered by the infant or beginner learner. In view of the characteristics of the vision for action and vision for perception systems, the establishment of a law of control reveals the integration between the two systems. Although a law of control itself represents the activity of the vision for action system, the set-up of action (i.e., the establishment of the control law) is constrained by the perception of what the situation affords (Goodale, 1998; Passingham & Toni, 2001; Van der Kamp et al., 2001). Hence, it is the integration between vision for perception and vision for action that is subject to changes due to the discovery of a law of control. Once a law of control is established, change over time can be induced by either a change of the optical variable (i.e., education of attention) or a change in the relation between the movement and optic variables (i.e., calibration) or both. It is vision for action that is liable to these types of changes.

If we weigh the empirical support of these three types of change of the visual control of movement during development and learning, only the support for the education of attention can reasonably be considered as credible. In contrast, the current empirical support for the discovery of the law of control and calibration is still largely lacking. Taking these reservations into account, the evidence suggests that both the form of change that occurs in the visual control of movement during development and the form of change that occurs during learning can be characterised as a change towards the use of more useful and specifying optic variables. Whether it concerned improvements during the development in the visual control of eye blinking (Kayed & Van der Meer, 2000) and catching (Van Hof & Van der Kamp, 2003) around 6 months, the development of the visual control of postural stability while standing or walking after 18 months of age (Stoffregen, Schmuckler, & Gibson, 1987) or improvements during the learning to visually control the return of an opponent's stroke in racquet sports (Carraugh & Janelle, 2002) or visually control the interception of a moving object (Jacobs, 2001), the observed changes were always found to be consistent with a change in optical variable use. Hence, even though the constraints that are imposed upon development and learning are vastly different, the form of the relationship between age and the change that occurs in the visual control of movement during development is similar to the relationship between the amount of

practice and the change that occurs in the visual control of movement during learning. That is not to say, however, that development and learning to visual control of movement are identical processes. The two may well be distinguished according to the (independent) variables that affect the course of change (e.g., the rate of change) during development and learning, as opposed to the occurrence of change (cf. Wohlwill, 1973). One such variable, to which we turn in the remainder of this article, may be related to how the infant's or learner's attention can be "educated." To this end, we first go over the recent debate pertaining to the focus of attention during learning to visually control goal-directed movements, and then explore whether similar attention-specific processes could mediate the course of development.

4. Accomplishing change when learning to visually control movement

4.1. *Explicit learning*

The teaching methods that are deemed most appropriate to reach the stage of automatic, smooth, effortless and fast control of goal-directed movements are closely linked with the investigators'—or teachers'—perspective on learning. In the tradition of the idea's of Fitts and Posner (1967), many investigators have argued that novice performance is based on explicit, declarative knowledge³ that is held in working memory and monitored in a step-by-step fashion (Beilock & Carr, 2001). The implication is an emphasis on instruction methods that induce verbal monitoring of the movement in the initial phase of motor learning. However, explicit learning is not a necessary feat. Automatic, smooth, effortless and fast control of goal-directed movements *can* also be acquired implicitly, that is, without an initial phase of explicit knowledge about the desired movement.

4.2. *Implicit learning*

Instead of trying to increase the novice's awareness of the desired movement, implicit learning methods aim to suppress the accumulation of explicit knowledge about how the movement should be executed. Several means have been employed to accomplish implicit learning; the use of cognitive secondary tasks while practicing the action (e.g., MacMahon & Masters, 2002; Masters, 1992), the use of an analogy that functions to integrate the complex structure of the desired movement in a simple metaphor (e.g., Liao & Masters, 2001), and the use of instructions that induce a focus on the external effects of the movement rather than the movement pattern per se (e.g., Wulf, Höß, & Prinz, 1998). Although strictly speaking the latter is perhaps not truly implicit learning, these methods have in common that they intend to draw the beginner's awareness away from movement execution. Learning without instructions (i.e., discovery learning) does not suffice, since it has been found to result in the accumulation of explicit knowledge (e.g., Masters, 1992). There is now a growing body of evidence that the (visual) control of goal-directed movements can not only be learned implicitly, but that it may even be beneficial over both traditional explicit and discovery learning. With the exception of the use of secondary tasks, implicit learning methods are shown to lead to higher levels of performance after the same amount of practice. In addition, implicit learning results in performance that better with-

stands psychological stress. That is, the liability to the well-known phenomenon of choking is diminished in comparison to explicitly learned movements, which are much more prone to the recurrence of explicit step-by-step monitoring (i.e., the reinvestment of verbalisable rules) as reflected in broken and stuttered movement execution.

Recently, Farrow and Abernethy (2002; see also Green & Flowers, 1991) have demonstrated that implicit learning can also invoke learners to attend to different optic variables (i.e., education of attention). Intermediate skilled junior players were required to return the opponent's tennis service on court under different visual occlusion conditions (i.e., a pair of liquid crystal spectacles were made opaque at various instances before and after racquet–ball contact of the service). The impact of both implicit and explicit learning on the ability to predict the direction of the serve was assessed. Two groups received physical and video-based perceptual training. The explicit learning group was instructed about the relationship between advance information and the service direction (see Section 3.2.2). The implicit learning group, in contrast, was instructed to estimate ball speed without receiving explicit verbalisable rules for the task. Seven of the eight learners in the implicit group, which actually had acquired less explicit rules, improved performance after training. This improvement involved the use of information from the phase before racquet–ball contact, that is, the key period that typically differentiates experts from novices and where racquet head motion and arm movement and speed best predict the future direction of the ball (Abernethy, 1990). The implication is that the implicit, but not the explicit, instruction led the learners to attend to more useful sources of information. Implicit learning removes the need for the beginning learner to describe verbally the specific information sources he needs to attend to, or the specific movements he or she has to perform (Magill, 1998).

4.3. *Implicit learning best befits vision for action*

Why would explicit and implicit learning methods affect the course of learning to visually control goal-directed movements in a different way? Unfortunately, except for propositions about the reduced liability for choking (e.g., Beilock & Carr, 2001; Masters, 1992), there are not many systematic attempts to explain why implicit learning would be advantageous (cf. Beek, 2000; Hodges & Franks, 2002). For instance, Wulf and Prinz (2001), who adhere to the theory of common coding for action and perception, argue that movements are planned and *controlled* by intended outcomes, which are the result of perceived environmental events produced by previous movements. Because only distal events allow for a commensurate common coding of perception and action, movements should be more effectively learned in terms of their effects rather than in terms of specific movement patterns. However, this hypothesis is open to many questions. Not the least is the hesitation uttered by the authors themselves: “Yet, because the theory is relatively abstract, it does not specifically predict the differential effects of external vs. internal foci” (Wulf & Prinz, 2001, p. 656).

In contrast to Wulf and Prinz (2001), we plea for the existence of anatomically and functionally separate, but interacting vision for action and vision for perception systems. Although both systems *can* be involved in the visual guidance of goal-directed movement, the vision for action system is designated to do so (see Section 2.2). Hence, the typical way to improve the visual control of movement, that is, to induce a change in the optic variables that are coupled to the movement variables or a change in the lawful relation between the two, would be to accomplish

change within the vision for action system. If we assume that such change is best achieved by a method that best fits the characteristics of the vision for action system, than implicit learning methods would be pre-eminent in accomplishing such improvements in the visual control of goal-directed movement. That is, given that on-line control of movement through the vision for action system is fast, short-lived and inaccessible to consciousness, a method that draws the beginner's awareness away from the execution of the movement would be preferable. It is difficult to conceive how the explicit step-by-step monitoring or use of verbalisable rules that is so characteristic for explicit learning could induce changes within the vision for action system.

That is not to say, however, that explicit learning strategies cannot bring about improvements in the visual control of movement. It can, but explicit verbalisations (and time delays) may perturb or even suppress the specialised vision for action system and enforce the involvement of the alternative route through the vision for perception system in the visual control of movement (see [Section 2.2](#)). Hence, explicitly learning—we hypothesise—would typically involve the route via the vision for perception system, where control is slow, explicit and based on allocentric as opposed to egocentric sources of information. In this case, learning implies some transfer of control from the vision for perception system to the specialised vision for action system. Moreover, automatic, smooth effortless and fast control initially acquired through explicit learning methods may remain particularly susceptible to control through the alternative vision for perception system (e.g., choking).

[Beek \(2000\)](#) suggested that “implicit learning is the rule, while explicit learning is the exception” (p. 552). We argue that it is the fit between the characteristics of implicit learning and the vision for action system that makes implicit learning more apt than explicit learning in improving the visual control of goal-directed movement. There is one more point we would like to stress before we explore the issue of implicit and explicit learning in the early development of the visual control of movement. We do not aim for a framework that saddles explicit learning with a supporting part. Bear in mind that we argued that the learning to set-up action (i.e., the discovery of the control law) reflects changes in the integration between vision for perception and vision for action (see [Section 3.3](#)). Explicit learning, therefore, may be particularly effective in learning what action is appropriate. PET-scan studies have shown a learning-related increase in the activity of the ventral vision for perception stream and a concomitant decrease in the activity of the dorsal vision for action stream, when subjects had to learn which of four gestures to perform when one of four non-sense figures was presented ([Passingham & Toni, 2001](#); [Toni & Passingham, 1999](#); see also [Lagarde, Li, Thon, Magill, & Erhani, 2002](#)). Interestingly, in most implicit learning studies participants were told or knew what action was appropriate (e.g., putting in [Masters, 1992](#) or slalom-like movements in [Wulf et al., 1998](#)), and hence learning was restricted to the refinement of the visual control of goal-directed movements.

5. Accomplishing change in the development of the visual control of movement

5.1. Introduction

In this final section, we explore how change in the visual control of goal-directed movements during development can be accomplished. We inquire whether the same implicit and explicit

processes of change that are found to affect the rate of learning may also mediate the course of development. Obviously, any definitive solution would be highly speculative. Our aim, therefore, is to only outline some of the building blocks that we think would eventually be part of the answer. To this end, we discuss the proposition that implicit as opposed to explicit learning is age-independent, which often goes hand in hand with the commonly accepted idea that implicit learning is the typical process that accomplishes developmental change in the visual control of goal-directed movements. We then explore whether explicit learning might also influence the course of development during infancy by pushing the hypothesis to its limits. A brief comparison between the changes that occur in the visual control of movement during development and learning brings the article to an end.

5.2. Implicit learning in development

Reber (1992) argued that implicit learning is a very basic process of considerable evolutionary antiquity that antedates explicit learning. Evolutionary older systems have greater stability. Therefore, implicit learning should show little in the way of inter-individual variability in comparison to the more recently evolved explicit learning processes. It is anticipated that implicit learning emerges early in development and shows few effects of age. Many authors have alluded to this idea (e.g., Beek, 2000; Bertenthal, 1996; Vinter & Perruchet, 2000). Bertenthal (1996), for instance, holds that “with exploration of their own actions and the environment, infants show increasing sensitivity to perceptual changes and finer control of actions that are guided by this information. In essence, then, learning is implicit or procedural: it is elicited by context, not by recall of explicit information about how to coordinate sensorimotor behaviors” (p. 453). This putative predominance of implicit learning processes in the development of the visual control of movement, or their presumed equality, fits with the proposal that the fast, implicit and short-lived vision for action processes are functionally dissociated from and follow different developmental trajectories than the explicit vision for perception processes (Bertenthal, 1996; Van der Kamp & Savelsbergh, 2000; see Section 2.3).

All the same, when it comes to hard data about implicit learning in the development of the visual control of movement, there is nothing like the empirical support that we found for learning to (visually) control movement. Nevertheless, a few studies do speak for the hypothesis that implicit learning processes in the context of the visual control of movement are age-independent and emerge early. Vinter and Perruchet (2000) examined the learning of new drawing behaviour of children between the ages of 4 and 10 years. Children received a training to fast and accurately trace a set of familiar geometrical figures where a point indicated where to start and an arrow specified in what direction to move. In one group a large percentage of these indications ran counter to a natural covariation that exists in drawing between the direction of movement and the starting position (e.g., a circle is drawn counter clockwise if the starting point is set above a virtual axis going from 11 o'clock to 5 o'clock). It was found that independent of age the children modified their natural drawing behaviour without being aware that they were doing so (as indicated by a questionnaire). Clohessy, Posner, and Rothbart (2001) showed that infants as young as 4 months could learn anticipatory eye movements to unambiguous sequences of targets (e.g., 1-2-3 1-2-3, etc.). Since learning in these infants was similar as in adults who were unaware of the sequence, the authors argued

that the infants' learning was based on implicit learning processes. It was only after 18 months that infants were able to learn to anticipate the more complex context-dependent sequences (e.g., 1-2-1-3-1-2-1-3, etc.), the performance of which was related to language ability (and perhaps explicit learning?).

In sum, the contribution of implicit learning processes in the development of the visual control of movement seems commonly accepted and can be theoretically underpinned. However, it would be premature to conclude that implicit learning processes can affect the course of the early development of the visual control of movement, not to mention the occurrence of developmental change.

5.3. *Explicit learning in development*

5.3.1. *Explicit learning: a stringent interpretation*

Explicit learning to visually control movement refers to improvements based on the accumulation of explicit knowledge about how the desired movement should be executed. Explicit knowledge is made up of information that we are aware of and, therefore, able to verbalise (Masters, 1992; see also Magill, 1998; Reber, 1992). If we adhere to this stringent definition then explicit learning can not take place before the end of infancy. Only after language ability develops, which in Western cultures often goes hand in hand with the introduction into some sort of physical education or training, children become susceptible to the type of verbal monitoring induced by explicit learning. Couched within the general evolutionary heuristic, the impossibility of explicit learning before the end of infancy could be considered advantageous. Explicit learning processes might have been eliminated from affecting the course of the early development of the visual control of goal-directed movements like grasping, walking and so on, because these basic milestones need more robustness in the face of pressure or disorders (Reber, 1992).

5.3.2. *Explicit learning: a soft interpretation*

We posit that explicit learning to improve the visual control of movement would typically involve the alternative route through the vision for perception system (Section 4.3). If this proposition is true, which remains to be proven, then we could perhaps loosen the criteria by which we can empirically establish whether the course of development of the visual control of movement can be affected by explicit learning processes. These criteria would not contain the requirement to be able to verbally articulate the information about the desired movement (e.g., Masters, 1992). Instead, the infant should in some other way be able to give evidence that she or he is aware of the information about the desired movement pattern (see also note 3). One possible implementation is to demonstrate that the infant is perceptually aware of his or her movements. To pursue the argument one step further, explicit learning processes in early development would imply a positive relationship between the infants' perceptual awareness of his or her movements and the improvements in the visual control of movement. We are not familiar with any research examining such relationship. Nevertheless, there are at least two prerequisites for such a relationship to be possible at all. First, infants should show some sort of perceptual awareness of their movements, and second, infants should be able to visually control their movements through the vision for perception system.

Infants' perceptual awareness of their movements can be assessed with preference looking procedures, which is presumed to tap vision for perception processes. Rochat and Morgan (1995; see also Rochat, 1998; Rochat & Striano, 2000) presented 3–5 month olds on-line with two different views of their own moving legs. The infants preferentially looked at the view in which the direction that the legs move was mirrored. A later study indicated that this looking preference reversed when a ball was presented next to one of the legs; the infants looked longer and kicked more when the non-mirrored view was presented (Rochat, 1998). Rochat suggests that the infants apparently “function interchangeably in relation to these two goals, which correspond to *doing* (perceiving-acting, i.e., kicking) and *probing* (recognizing and representing, i.e., exploring novel, unfamiliar calibration of the legs in relation to familiar one)” (Rochat, 1998, p. 107; italics in original). In other words, at the age of 3 months, infants have some perceptual awareness of the direction in which their legs move, and this awareness appears to be independent from the visual control of those kicking movements. Hence, at 3 months, the first prerequisite that some type of explicit learning processes may be feasible seems met (see also Van der Meer, Van der Weel, & Lee, 1995).

What about the second prerequisite, the ability to visually control movement through the vision for perception system? The introduction of a temporal delay between the detection of information and the initiation of the movement is one of the specific conditions under which control through the vision for perception can be induced (see Section 2.2). Two types of experimental manipulation in infant studies provide insight in this matter; reaching in the dark and reaching for temporally occluded moving objects. It is a matter of dispute at what age infants can reach for non-sounding objects that are invisible throughout the entire reach, including its initiation. Recently, McCarty, Clifton, Ashmead, Lee, and Goubet (2001) have found that it is only at 9 months that infants reach when vision of the object is removed *prior* to reach onset (cf. Hood & Willats, 1986; Jonsson & Von Hofsten, 2003; Van der Meer et al., 1994). Unfortunately, however, this and other studies do not provide sufficiently detailed kinematics to assess whether errors in reaching were aligned with an allocentric frame of reference, as would be predicted were reaching controlled through the vision for perception system (see Section 2.2).

In sum, there is some empirical support for the contention that infants can be aware of their movements, but little when it comes to infants' visual control of movements through the vision for perception system. However, the evidence so far is not contradictory either. It appears not completely unfeasible, therefore, that explicit learning processes (i.e., in a less strict interpretation) can occur early in development. Perhaps we could induce them by drawing on observations that for infants between 9 and 12 months, adults can, by changing gaze coupled with a head turn and/or a pointing gesture and later with verbal encouragement, direct infants' visual attention (e.g., Butterworth & Cochran, 1980; Flom & Pick, 2003).

6. Concluding remarks

In our inquiry into the changes of the visual control of goal-directed movement during development and learning, we felt impelled to bring together theory and observations from

sometimes fairly disparate fields of study. Although such a merging of ideas can be (and hopefully is) very fruitful, it has the drawback that many of the hypothetical relations still need empirical verification—or falsification. Any definitive conclusions, therefore, would be premature. Notwithstanding this state of affairs, it appears justified to assume that both the development and learning of the visual control of goal-directed movements are governed by a change toward the use of more useful and specifying optic variables. Hence, whether it concerns a change that occurs in the vast majority of infants under the most varied conditions and within a fairly narrowly delimited age period (i.e., development), or whether it only concerns change observed in a few individuals subjected to specific conditions (i.e., learning), the change often involves a change in optic variable use. We have argued that this makes intuitive sense given the organisation of the visual control of movement. The on-line, fast, short-lived and implicit vision for action system, to which we are referring, provides important constraints for the manner in which change can be accomplished, both during development and learning. It is, therefore, that implicit learning processes, in which the learner's awareness of how the desired movement should be executed is minimised, are pre-eminent in inducing changes in the visual control of movement. This needs to be qualified for the age-related changes, because the empirical support for the effect of implicit processes in the course of development is meagre. Notwithstanding this, it seems much more reasonable that it is explicit learning that makes the difference between development and learning to visually control movement. However, if one is prepared to use the ability to demonstrate perceptual awareness as a criterion then the contribution of explicit learning processes in the development of the visual control of movement, even during infancy, cannot be excluded.

Notes

1. One may want to argue that even novices have already discovered what actions are appropriate simply by listening to the instructions of the investigator. The participants of the experiment know that they have to return the ball. However, to the extent that they still have to find out, for instance, whether the ball should be returned either with a backhand or forehand stroke, there are still affordances to be discovered.
2. We follow Jacobs and Michaels (Jacobs, 2001; Jacobs & Michaels, 2002) who in the context of perception refer to a variable as specifying only if it specifies the property that the perceiver intends to perceive, and to a non-specifying variable when it does not specify that property. Previously, the more arbitrary terms higher and lower order variables have been used to refer to a similar distinction (e.g., Kaye & Van der Meer, 2000; Michaels & De Vries, 1998; Van der Kamp, Savelsbergh, & Smeets, 1997).
3. Magill (1998, p. 105) defines explicit knowledge as “information we can verbally describe, or in some other way give evidence that we are ‘consciously aware of’ the information.” The second part of this definition may provide the opportunity to apply the concept of explicit knowledge in early human development as well (see section 5.3.2).

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