Chapter 7

General Discussion

On the use of visual information in infant reaching actions
After testing more than 200 infants and analyzing thousands and thousands of reaching movements, this thesis has come to its final chapter. The only thing left is to summarize the findings of the previous chapters, formulate conclusions, and to (re-) assess the theoretical framework based on the presented findings and recent findings in adult research. As is always the case when doing good research more questions arise than are answered and, thus, this epilogue concludes with providing some directions for future research.

**Summary of the findings**

The aim of the present thesis was to shed light upon the early development of the use of visual information for the perception of objects, events, places, and what they afford for action and for movement control. This was motivated by a currently dominant adult-paradigm, the two-visual systems model (Goodale & Milner, 1992, 2004b; Milner & Goodale, 1995, 2008), which suggests a dissociation in information exploitation for these processes (Michaels, 2000; van der Kamp, Oudejans, & Savelbergh, 2003; van der Kamp, Savelbergh, & Rosengren, 2001). More specifically, it is argued that the perception of objects, events, places and what they afford for action mainly relies upon allocentric (i.e., context-dependent) sources of information and is supported by the ventral vision for perception system. By contrast, the control of visually guided movements is reliant on egocentric (i.e., context-independent, absolute metrics) sources of information and engages the dorsal vision for movement system. Yet, this is strictly limited to movement execution, the selection of an appropriate mode of action is thought to involve the ventral vision for perception system (Milner & Goodale, 2008; van Doorn, van der Kamp, & Savelbergh, 2007).

A thorough outline of this theoretical framework was provided in Chapter 2, which also reviews prior work on whether this informational dissociation might be present during the first year of life. To this end, it was explored whether findings in early vision for perception (i.e., habituation and preference looking studies) are consistent with the use of allocentric information and, vice versa, whether findings concerning vision for movement (i.e., reaching and visual tracking) are consistent with the use of egocentric sources of information. Although circumstantial (i.e., comparisons between vision for perception and vision for movement always involved different studies in which experimental settings and procedures were often quite different), the findings indeed pointed to an early dissociation in information usage for vision
for perception and vision for movement. For instance, in infants as young as three months, visually guided reaching seems primarily reliant on visual information that specifies the relation between the object and the infant (i.e., egocentric information; von Hofsten, 1983). It is only at later ages that allocentric information may start to contribute. By contrast, vision for perception (i.e., discriminating relative velocity or motion direction) mainly exploits allocentric sources of information in 3-month-old infants (e.g., Wattam-Bell, 1996a, 1996b), and it is only beyond this age that egocentric information may come to play a role as well. However, given the indirect nature of the comparisons, the experimental work in chapters 4 to 6 assessed more directly whether the purported dissociation between vision for perception and vision for movement and their reliance on visual information exists in early infancy.

One aspect that is thought to be supported by vision for perception is the selection of an appropriate mode of action, for instance, performing a reaching movement with one or two hands (e.g., van Doorn et al., 2007). In Chapter 4 it was examined whether this action mode selection and the subsequent movement control are adapted to object size when reaching for different-sized objects in 5- to 9-month-old infants. Also, it was assessed whether these processes are mutually constraining or are more precisely described as independent. In line with previous observations (e.g., Newell, McDonald, & Baillargeon, 1993; Newell, Scully, McDonald, & Baillargeon, 1989a; Siddiqui, 1995), infants adapted their action modes to object size from 5 months onwards; i.e., reaching with one hand in case of small objects and reaching bimanually in case of larger objects. In addition, infants this young increasingly controlled their bimanual hand-aperture to object size during the approach towards the object (i.e., before contact). Interestingly, however, these processes were not mutually constraining. That is, infants who display adaptive action mode selection relative to the size of the object, not necessarily scale their hand aperture to object size, and vice versa. Within the context of the two-visual systems model, this may imply that beyond 5 months of age, vision for perception (as indicated by action mode selection) and vision for movement (as indicated by movement control), are dissociated. Yet, whether this dissociation is information-based remains unclear and was therefore addressed in Chapters 5 and 6.

According to the two-visual systems model, the dissociation in information usage entails that vision for perception mainly relies on allocentric information, whereas vision for movement primarily exploits egocentric sources of information. In Chapter 5, it was assessed whether infants’ reliance on allocentric information sources is indeed
limited to action mode selection (i.e., reaching with one or the other hand) or whether this information is exploited for movement control (i.e., reaching kinematics) as well. Six- to 10-month-old infants were presented with laterally approaching objects at two speeds against a stationary or moving background (i.e., manipulating allocentric information that specifies object velocity relative to its background). In line with previous observations, infants’ action mode selection and movement control were constrained by object velocity relative to their action capability (Out, Savelsbergh, & van Soest, 2001; van Hof, van der Kamp, Caljouw, & Savesbergh, 2005). More specifically, with higher object speed, infants were more inclined to reach with their contralateral (i.e., right) hand, probably because this affords them more time to intercept the object, albeit that this effect was less pronounced with increasing age. In addition, an increase in object velocity resulted in a decrease in reach duration, number of movement units, and deceleration phase of the reach, and an increase in mean velocity. Importantly, background motion (i.e., allocentric information) also affected infants’ reaching modes. Yet, it was only at 10 months that the effects of background were consistent with the use of allocentric information (i.e., reaching with the contralateral hand in case of a higher relative velocity). Although reaching modes were also affected by background motion at 6 months, these effects were not in complete agreement with the use of allocentric information. Moreover, infants’ movement control remained unaffected by the background motion with the exception of the timing of movement onset, which showed effects of background motion when time constraints were clearly highest (i.e., reaches with the ipsilateral hand for the fastest moving objects). It was in these cases that infants initiated their reaches earlier (i.e., at a larger time to contact) when object velocity relative to its background was low. Together, and in line with the two-visual systems model, these findings indicate that action mode selection is consistent with the use of allocentric information at 10 months of age. In addition, movement control remained unaffected, suggesting that allocentric sources of information are not exploited during the execution of the reach. However, and deviating from the two-visual systems model, infants’ movement onset was affected by background motion (i.e., allocentric information). The current findings, then, imply that the use of visual information for vision for perception and vision for movement is largely, but not completely, dissociated at 6- to 10-months of age.

Vision for perception is not only presumed to contribute to action mode selection (i.e., how to interact with an object), but also engages in the perception of the affordance
of an object (i.e., whether or not to interact with an object). Chapter 6 focused on the latter. Its aim was to assess 6- to 7-month-old infants’ reliance on visual information for affordance perception (i.e., whether or not to reach for a certain object) and movement control. To this end, infants were presented with two equidistant objects in front of an illusory background that makes the objects appear to be located at different distances. In line with previous observations, infants preferred to reach for the apparently closer object (i.e., which more strongly afforded reaching) as compared to the perceptually distant object (Kavsek, Granrud, & Yonas, 2009; Yonas, Elieff, & Arterberry, 2002). By contrast, movement control was only affected by real changes in object distance (i.e., higher peak velocity and increase in movement units) and not by changes in relative object distance – not even for infants who clearly relied upon this information to guide their preferential reaching. These findings, therefore, strongly suggest differential information usage for affordance perception (i.e., as indicated by a preference to reach for the perceptually closer object) and movement control, at least beyond 6 months of age. Hence, in terms of the two-visual systems model these findings point to an early dissociation between vision for perception and vision for movement.

So far, the focus has been on the dissociation between vision for perception and vision for movement. Yet, it should be clear that these systems must work closely together and serve complementary functions. For instance, if one system is compromised, the other system may become more dominant. A frequently investigated scenario is the introduction of a temporal delay between object presentation and movement onset, which perturbs the online pick-up of information for controlling movements. It is in these situations that vision for perception contributes to the control of movement, which is indicated by movement control being more reliant on allocentric information (e.g., Hu, Eagleson, & Goodale, 1999; Milner & Goodale, 2008; Westwood & Goodale, 2003; Westwood, McEachern, & Roy, 2001). As such, studying young infants’ visual tracking and reaching for temporarily occluded objects might provide insight into the early interactions between the two visual systems. A review of the literature (see Chapter 2) suggested that it is around 4 to 5 months that infants show anticipatory tracking and reaching for objects that are obscured from sight for a brief period of time (e.g., Jonsson & von Hofsten, 2003; Rosander & von Hofsten, 2004). In terms of the two-visual systems model, this might suggest that it is around that age that vision for perception may contribute to movement control.

Indeed, given the presented findings of chapters 4 to 6, which point to a
dissociation between vision for perception and vision for movement around 6 months of age, the issue of the interaction between the two systems becomes relevant. Chapter 3 speaks to this issue by exploring 7- to 9-month-old infants’ anticipatory reaching in occlusion situations. In line with observations in adults and the prediction from the two-visual systems model (see e.g., Bridgeman, Gemmer, Forsman, & Huemer, 2000; Bruno, Bernardis, & Gentilucci, 2008), occlusion duration seems the primary constraint on infants’ anticipatory reaching. That is, with longer occlusion durations fewer anticipatory reaches are made, although the adverse effect of longer occlusion durations diminishes with increasing age. Regarding the two-visual systems model this may indicate that vision for perception contributes to the control of movement during infancy. Although this interaction is relatively fragile at 7 months of age, it stabilizes until at least 11 months.

**Differential use of visual information in early infancy**

This thesis investigated the early development of the use of visual information for vision for perception (i.e., action mode selection and affordance perception) and vision for movement. More specifically, it was aimed to assess whether these processes and their reliance on visual information is dissociated. Together, the findings provide evidence that vision for perception and vision for movement (1) are separate processes, and do not mutually constrain each other’s development (Chapter 4), and (2) rely upon different sources of visual information around 6 months of age (Chapters 5 and 6). As such, the findings point to an early dissociation between vision for perception and vision for movement during early infancy.

The finding that vision for perception and vision for movement are separate and not mutually constraining in development indicates that the development of either system is not a necessary cause for the development of the other (i.e., that one cannot develop without the other). That is not to say, however, that they may not be sufficient causes in each other’s development. That is, even though the development of one system does not depend on the development of the other, it may be that the development of one system does contribute to or facilitate the development of the other. In other words, although the developments of vision for perception and vision for movement are not intrinsically linked and may follow their own developmental trajectory, they can influence each other (Atkinson, 2000; Babinsky, Braddick, & Atkinson, 2012; Bertenthal, 1996; DeLoache, Uttal, & Rosengren, 2004; Street, James, Jones, & Smith,
2011; van der Kamp & Savelbergh, 2000; see also future directions, p. 205).

Indeed, the fact that the use of visual information is largely dissociated for vision for perception and vision for movement also is supportive of such a claim. That is, it was shown in Chapters 5 and 6 that vision for perception (i.e., affordance perception and action mode selection) was reliant upon allocentric sources of information, whereas movement control exploited egocentric sources of information (or at least remained unaffected by changes in allocentric information). Interestingly, movement onset was found to be affected by and consistent with the use of allocentric (background) information in 10-month-olds (Chapter 5). This finding suggests that the use of visual information for vision for perception and movement control is perhaps not completely dissociated at 10 months. In this respect, it is not fully apparent whether, and if so at what age, the dissociation is complete. Indeed, even in adults the dissociation in information usage may not seem to be absolute with respect to movement onset (Smeets & Brenner, 1995).

**Differential information use and the two-visual systems model**

Over the last two decades, research in adults has provided progressively more evidence supporting the notion of two functionally and neuroanatomically dissociated, but interacting, visual systems (e.g., Ganel, Tanzer, & Goodale, 2008; Milner & Goodale, 2008; Rossetti & Pisella, 2002; van Doorn et al., 2007). Indeed, the amount of work in support of the two-visual systems model is still growing, but so do reports that are not in complete agreement with the model (e.g., Franz, Hesse, & Kollath, 2009; Schenk, 2012; Schenk & McIntosh, 2010; Smeets & Brenner, 2006). One of the main critiques is perhaps the specificity of information use relative to the function of the two visual systems. That is, do visual perception (including affordance perception and action mode selection) and movement control rely exclusively on allocentric and egocentric sources of information (resp.), or, alternatively, is it more likely that in some circumstances egocentric information also contributes to visual perception and that allocentric information is also involved in the control of movement? Indeed, based on the available evidence, it seems that a one-to-one mapping from visual information to function is not viable (e.g., Bruno & Franz, 2009; Franz et al., 2009; Glover & Dixon, 2001; Schenk & McIntosh, 2010; Smeets & Brenner, 1995, 2006). This is also suggested
by some of the evidence in the present thesis, most notably the finding in Chapter 5 that movement onset was reliant on allocentric information. Similarly, the reviewed findings in Chapter 2 show that, although allocentric information is the first to be used for visual perception, at later ages egocentric information sources can be exploited as well. In addition, the fact that vision for perception is involved in various aspects of action (i.e., action mode selection), which likely includes movement control in the case that vision for movement is perturbed, rather than in visual perception only, is also supportive of such a claim. In other words, vision for perception and vision for movement, and the neural substrates (i.e., ventral and dorsal stream), are perhaps better considered as perceptual systems that are dedicated to the pick-up of certain types of visual information that operate at certain speeds than uniquely supporting different functions (Madary, 2011). That is not to say, however, that system and function do not closely map. For instance, movement control normally requires the pick-up of instantaneously available egocentric information, while the perception of objects, events, and places often is relative to their surroundings. Yet, the relation between information and function (and similarly, the relation between the two systems and function) is perhaps less strict as Milner and Goodale originally presumed (Schenk & McIntosh, 2010). That is, the dissociation between vision for perception and vision for movement (and, thus, the ventral and dorsal stream) may be better characterized as an information-based dissociation, instead of a functional distinction.

If true, it is important to evaluate the degree to which the present findings are dependent on a strict notion of the two-visual systems model as proposed by Milner and Goodale (1995, 2008), which suggests a functional dissociation between vision for perception and vision for movement. Clearly, this thesis was inspired by the model, but the findings do not depend on its validity. Rather, the most important finding is that infants’ information usage for affordance perception and action mode selection on the one hand and movement control on the other are different. From an ecological point of view, these findings can be interpreted as the perceptual system being adaptive relative to its function, that is, exploiting different sources of visual information for different purposes. In case of movement control, the perceptual system mainly, but not exclusively, detects egocentric information, whereas it detects allocentric information in case of visual perception tasks (including affordance perception and action mode selection).
Future directions

Based on the presented findings of the current thesis, there are many directions for future research that might be explored. In what remains three of these directions will be elaborated on. Firstly, given the behavioral nature of the current findings, it would be worthwhile to extend the current research with neuropsychological measures. This is the more interesting given the growing debate on the validity of the two-visual systems relative to their supposed functions. After all, this might reveal whether there are differential involvements of the dorsal and ventral streams during movement control and affordance perception or action mode selection in early development, or whether, as is proposed above, this differentiation is information-based rather than yielding a functional dissociation.

Secondly, in order to portray individual trajectories of the developments of vision for perception and vision for movement longitudinal measurements, as opposed to the cross-sectional measurements performed in this thesis, are needed. This might reveal in much more detail to what extent and how the developments may influence one another on a developmental time scale. Additionally and related to this, it is worthwhile to explore mutual influences of the two systems during the process of learning. Indeed, recent observations suggest that after brief periods of learning, the two visual systems might mutually constrain each other. For instance, after being presented with a few related events, 4-month-old infants performed more anticipatory eye movements (Johnson & Shuwairi, 2009). Moreover, 4.5-month-old infants who experienced causal effects of one’s movements (i.e., displacing objects by the use of sticky mittens) enhanced their ability to discriminate between causal and non-causal events (i.e., a stationary object that started to move after it was contacted by a moving object; Rakison & Krogh, 2011; van Hof, van der Kamp, & Savelsbergh, 2008). These findings suggest that vision for perception and vision for movement may induce adaptive changes onto each other on longer time scales.

Finally, although the present thesis suggests a dissociation between vision for perception and vision for movement around six months of age, the question remains as to how the two visual systems originate. Hence, future efforts should be directed to explore infants’ reliance on visual information for vision for perception and vision for movement at even younger ages (i.e., before visually guided reaching emerges). Studying infants’ eye movement control (i.e., visual tracking) might provide a useful method in order to portray the development of the use of visual information for
vision for movement during the first months of life (e.g., Rosander & von Hofsten, 2004; von Hofsten & Rosander, 1996). Moreover, habituation and preference looking methods may be used to reveal differential involvements of egocentric and allocentric information in the early development of vision for perception (see also Chapter 2).