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Concurrent Processing of Optic Flow and Biological Motion

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The concurrent processing of optic flow and biological motion is crucial for navigating to a destination without colliding with others. Neuroimaging studies and formal models have provided evidence for distinct neural mechanisms involved in processing the 2 types of motion. It may, therefore, be possible to process both types of motions independently. To test for possible interferences at the behavioral level, we conducted a dual task paradigm in which we presented a point-light walker in a flow field that simulated forward motion. Observers judged both the articulation of the walker and the heading direction. We found that varying the difficulty of one task had no effect on the performance of the other task, arguing against interferences. Performance in the biological motion task was similar in dual and single task conditions. For the heading task, concurrence costs were observed when the heading task was difficult but not when it was easy. Concurrence costs did not depend on practice effects, effects of specific motor responses, and incidental processing of biological motion. In line with neuroimaging studies and formal models, our results argue not only for independent processing of optic flow and biological motion but also for concurrence costs affecting heading performance.

Keywords: biological motion, optic flow, dual task, heading perception, motion perception

Moving through the environment requires mechanisms that enable us to remain spatially oriented to navigate to our destinations. An important cue for navigation is optic flow (Cutting, Springer, Braren, & Johnson, 1992; Gibson, 1950; Lappe, Bremmer, & van den Berg, 1999). As we move, we often encounter other moving people and animals. Consequently, the concurrent processing of optic flow and the biological motion produced by other moving people is a common challenge for the visual system in everyday life. In the present study, we investigated whether concurrent processing of the two types of motion leads to interferences, or whether independent processing is possible. We measured potential interferences using dual task paradigms.

In dual task paradigms (e.g., Kahneman, 1973; Kalsbeek & Sykes, 1967; Norman & Bobrow, 1975), observers are required to perform two tasks concurrently. Interference is inferred when varying parameters that affect the difficulty of one task also affect performance on the other task, or when allocating attentional resources to one task decreases performance on the other task (Norman & Bobrow, 1975). Poorer performance on a dual compared to a single task alone is not sufficient to imply interference. This is because coordinating the performance of two concurrent tasks might require resources itself and therefore decreases dual task performance with respect to single task performance. This is commonly referred to as “concurrence cost” (Gopher & Navon, 1980). Independent processing, by comparison, can be inferred when performance in one task is independent of variations of difficulty of the other task or attentional shifts. Interferences can, in principal, occur at all stages of visual processing (Franconeri, Alvarez, & Cavanagh, 2013; see Marois & Ivanoff, 2005, for a review). Critical stages for interference are sensory processing, visual short-term memory (STM; Cowan, 2001), and the response selection stage (Pashler, 1994).

Previous research has reported decreased performance in dual task compared to single task settings for both optic flow and biological motion tasks. Royden and Hildreth (1999), for example, combined an optic flow with an object tracking task and found that dual task performance was worse than single task performance.

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The present study is part of a larger research project on the visual ecology of motion perception. Motion of oneself (optic flow) and the motion of others (biological motion) are the two main generators of retinal motion. Past research has shown fundamental differences between their computational requirements, perceptual mechanisms, and their neural correlates. Ecologically relevant situations containing both types of motion have seldom been thoroughly investigated, however. Computational considerations suggest, on the one hand, that the two types of motion will inflict problems onto each other since they violate respective computational prerequisites (cf. Riddell & Lappe, 2017, 2018). On the other hand, because both are supported by distinct perceptual mechanisms there may be synergies and cross talk between the systems. Dual task experiments thus provide a critical test of potential interferences from a theoretical point of view. They are also of high practical relevance. Everyday-life activities such as participating in traffic often require concurrent performing of self-motion and biological motion analyses.

Some of the data presented here were presented at the European Conference on Visual Perception in 2018 and the Psychonomics Society Meeting in 2018.

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The decline in performance in the object tracking task, however, was larger than in the optic flow task. Thornton, Rensink, and Shiffrar (2002) combined a biological motion task in which observers discriminated the walking direction of a person with a shape discrimination task. They found that performance on the biological motion task was worse when the shape discrimination task was performed concurrently in comparison to the condition in which only the biological motion task was performed. Whether concurrent processing of biological motion and optic flow leads to dual task interference is currently unclear. There is, however, evidence from neuroimaging studies and conceptual models describing the processing of the two types of motion that suggested that independent processing might be possible.

At the cortical level, neuroimaging studies have shown that when two different single tasks elicited responses in similar brain areas, dual task interference was larger than when single tasks elicited distinct response patterns (Alavash, Hilgetag, Thiel, & Gießing, 2015; Nijboer, Borst, van Rijn, & Taatgen, 2016). With respect to biological motion and optic flow, previous research provided evidence for largely separate networks specialized in the processing of biological motion and optic flow. With respect to optic flow, Morrone et al. (2000; see Greenlee, 2000, for a review) showed that a functionally distinct subregion within the human MT/V5 complex responded selectively to displays with expanding radial optic flow. This region was found to be separate from another subregion within MT/V5 that responded to translational motion. Peuskens, Sunaert, Dupont, Van Hecke, and Orban (2001) found similar specialization within human MT/V5. In addition, they found that early visual areas, the dorsal intraparietal sulcus and motor areas responded to optic flow stimuli. In line with these findings, Smith, Wall, Williams, and Singh (2006) described functional specialization within MT/V5 for translation (human MT) and expanding motion (human MST). Further areas were found to be involved in processing optic flow. Koyama et al. (2005) found that human V3A was selective to the retinotopic location of the focus of expansion of a flow field. Previously, this area was found to be sensitive to visual motion (Tootell et al., 1997). Wall and Smith (2008) found selective responses to optic flow that were consistent with self-motion in an area within the visual cingulate sulcus and an area in the anterior portion of the intraparietal sulcus. Pitzalis et al. (2010) found that human V6 located in the occipito-parietal sulcus responded to optic flow fields.

With respect to biological motion, the superior temporal sulcus has been consistently found to be responsive to biological motion but not to other types of visual motion such as translational motion (Beauchamp, Lee, Haxby, & Martin, 2002, 2003; Grossman & Blake, 1999; Grossman et al., 2000, 2005; Hirai, Fukushima, & Hiraki, 2003; Krakowski et al., 2011; Michels, Kleiser, de Lussanet, Seitz, & Lappe, 2009; see Blake & Shiffrar, 2007, for a review). Furthermore, areas along the ventral pathway such as the fusiform and occipital areas specialized in the processing of faces also showed selective responses to biological motion (Grossman & Blake, 2002; Michels et al., 2009). Neuropsychological studies with patients with damage to the parietal lobe revealed selective deficits in the processing of biological motion. This indicated involvement of attention-related parietal areas for processing biological motion (Battelli, Cavanagh, & Thornton, 2003; Pavlova, Lutzenberger, Sokolov, & Birbaumer, 2004). Further studies found evidence for the involvement of premotor areas (Gilaie-Dotan, Kanai, Bahrami, Rees, & Saygin, 2013; Saygin, Wilson, Hagler, Bates, & Sereno, 2004; Saygin, 2007), the cerebellum (Sokolov, Gharabaghi, Tatagiba, & Pavlova, 2010), kinetic occipital area (Vaina, Solomon, Chowdhury, Sinha, & Belliveau, 2001), and the lingual gyrus (Servos, Osu, Santi, & Kawato, 2002).

At the conceptual level, substantially different models were developed to describe the mechanisms underlying biological motion and optic flow processing. Models describing optic flow processing rely on static points of the environment and how they move across the retinae when the observer is moving (Lappe & Rauschecker, 1993; Longuet-Higgins & Prazdny, 1980; Perrone & Stone, 1994; see Raudies & Neumann, 2012, for a review). Biological motion processing, in contrast, is deducted from prior knowledge about the specific shape and the motion pattern of humans and animals (Beintema & Lappe, 2002; Giese & Poggio, 2003; Lange & Lappe, 2006; Theusner, de Lussanet, & Lappe, 2014).

Largely separated specialized cortical networks and substantially different models describing brain mechanisms of processing biological motion and optic flow may suggest independent processing of the two types of motion. There is, however, evidence for preferential processing of biological stimuli in the visual system which could affect the concurrent processing of optic flow. In general, the human visual system is highly sensitive to biological shape and motion (Beintema & Lappe, 2002; Cavanagh, Labianca, & Thornton, 2001; Troje & Westhoff, 2006). Human shape and motion can be inferred from impoverished stimuli in which only moving markers attached to the joints are visible (point-light walkers [PLW]; Johansson, 1973). Detection of humans in natural scenes is efficient and attracts eye fixations (Bindemann, Scheepers, Ferguson, & Burton, 2010; Mayer, Vuong, & Thornton, 2015, 2017). Furthermore, human observers are more sensitive to the motion of other humans than to the motion of animals (Pinto & Shiffrar, 2009). With respect to attentional processes, both human shape and motion are salient. Downing, Bray, Rogers, and Childs (2004) showed that images of the human body captured attention. Thornton and Vuong (2004) found that human motion was processed incidentally and that it interfered with other visual tasks.

In general, independently moving objects in the environment challenge the processing of optic flow that is due to self-motion (Warren & Saunders, 1995). Because of the high sensitivity of the visual system to biological stimuli they could be a critical source of uncertainty for processing optic flow due to self-motion. As reviewed above, biological stimuli could capture attention (Downing et al., 2004; Thornton & Vuong, 2004) and might therefore limit the capacity to process optic flow. This hypothesis is in line with findings for coherent motion processing. Fujimoto and Yagi (2008) showed that perception of coherent motion was biased by the presence of biological motion. When an intact PLW was present in a coherently moving dot field the perceived motion direction of the dot field was biased in the walking direction of the PLW. No such effect was found when a scrambled PLW was present in the dot field (Fujimoto & Yagi, 2008). The movement of other beings, however, can also provide information about the sources of the motion on the retinae. Riddell and Lappe (2017) showed that human observers were able to infer simulated self-motion even when the only source of information was provided by a single PLW. They showed that observers used cues about biological motion to solve ambiguous information about optic flow due to self-motion. It was suggested that this was possible because human motion is highly familiar with respect to articulation and the associated translation speed (Masselink & Lappe, 2015; Thurman & Lu, 2016).

Previous behavioral (e.g., Royden & Hildreth, 1999), conceptual (e.g., Beintema & Lappe, 2002; Giese & Poggio, 2003; Lange & Lappe, 2006; Lappe & Rauschecker, 1993), and neuroimaging (e.g., Grossman et al., 2000; Peuskens et al., 2001) research provided diverging evidence as to whether or not optic flow and biological motion might interfere with each other during concurrent processing. In the present study, we conducted experiments in which we presented human observers with optic flow fields and PLWs. We measured the accuracies on heading and articulation judgments in dual task settings while varying either the difficulty of the heading task or the difficulty of the walker task. If biological motion and optic flow are processed independently, we would expect that changing the difficulty of one task would not affect accuracy on the other task beyond potential concurrence costs (Gopher & Navon, 1980). If interferences were to occur, however, we would expect decreasing performance on one task caused by increasing difficulty on the other task. We also compare dual task performance with performance in each task performed alone. Additional control experiments tested for practice effects, incidental processing of biological motion, effects due to the particular response paradigm used in the present studies and overall task difficulty.

Method

Participants

We conducted a power analysis using G*Power (Faul, Erdfelder, Buchner, & Lang, 2009) to estimate the optimal number of participants for our experimental design. The analysis revealed that for detecting a small to moderate effect of $\eta_p^2 = .35$ with a power of 80% (Riddell & Lappe, 2018) a sample size of 10 participants was optimal. Ten participants (five female, five male; average age = 24 years, *SD* = 9 years) with normal or corrected-to-normal vision participated in the experiments. Two of the authors (Katja M. Mayer and Hugh Riddell) were included in the study. The remaining participants were informed that the study investigated interferences between biological motion and optic flow processing but were naive to specific hypotheses. All participants gave informed consent prior to participating. All participants were lab members and experienced with psychophysical experiments. Originally, 11 participants were recruited for the study, but one male participant dropped out before the experiments with variation of heading difficulty were finished and was therefore excluded from all analyses. The study was approved by the Ethics Committee of the Department of Psychology and Sports Science of the University of Muenster.

Setup

Experiments were run in a dark, quiet lab. Participants were seated on a chair at a distance of 100 cm from a 200 cm × 248 cm screen. The eye-height was approximately 140 cm. Experiments were presented on an Apple MacBook Pro with an Intel Iris Pro built-in graphics card and back-projected onto the screen using a VDC Display Systems Marquee 8500 projector (resolution of 600 × 800 pixels, refresh rate of 60Hz). Participants were asked to fixate on the screen, but head and eye movements were not constrained. Stimuli were generated in Matlab (Mathworks, Natick, MA) using the Psychtoolbox 3 extension (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997) as well as the OpenGL libraries (Version 2.1). Responses were collected from a standard Apple keyboard.

Stimuli

The stimulus was a scene including a PLW and a flow field formed by dots surrounding the PLW. The scene was rendered as if it was viewed through a "virtual camera" (see Riddell & Lappe, 2017). The scene was defined in terms of a coordinate system with its origin at the location of the camera (i.e., the eyes of the observers). The z-axis extended in depth, the x-axis horizontally, the y-axis vertically. An example stimulus is shown in Figure 1. We used a PLW obtained with kinematic data recording from a male human (de Lussanet et al., 2008; Riddell & Lappe, 2017). The PLW consisted of 12 dots marking feet, knees, hips, wrists, elbows, and shoulders of the PLW. Participants viewed the PLW's profile. The PLW faced to the left on half of the trials and to the right on the other half of the trials. The PLW was displayed at a fixed location in the scene while articulating in place, in a similar manner to walking on a treadmill at a velocity of 1.2 m/s. The PLW had an on-screen width of 10.5 cm (6° of visual angle) and an on-screen height of 17.5 cm (10° of visual angle). The PLW was rendered to appear to be at a distance of 150 cm in front of the observer. In six experiments, the PLW always consisted of 12 dots. Difficulty of the heading task was manipulated by varying simu-

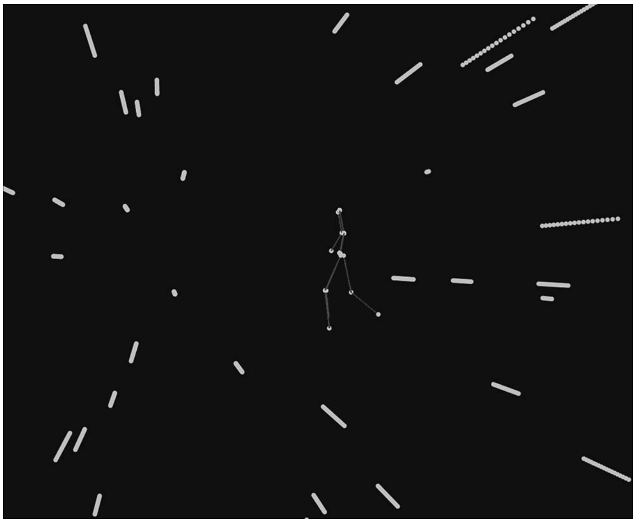

Figure 1. One frame from the animation showing a point-light walker with an overlay of 18 frames of the flow field that simulated forward motion of the observer. The point-light walker articulated forward or backward while fixed in the center of the screen as if on a treadmill. The contrast of the dots of the point-light walker and the number of the dots of the flow field are optimized for display purposes in this figure. The lines indicating the shape of the point-light walker were not shown in the experiments.

lated heading speed between 0.05 m/s and 0.48 m/s. In four experiments, the heading speed was always 0.05 m/s. Difficulty of the walker task was manipulated by varying the number of dots forming the PLW (Beintema, Georg, & Lappe, 2006; Neri, Morrone, & Burr, 1998). This means that the PLW consisted of between five and 12 dots. This allowed for manipulating difficulty of the walker task while keeping movement patterns ecologically valid. Manipulating difficulty of the walker task by increasing or decreasing articulation speed may have led to unfamiliar movement patterns and could have affected normal processing of the PLW (Giese & Lappe, 2002; Lange & Lappe, 2006). The subset of dots that formed the PLW on a given trial was randomly selected. In the last experiment, heading speed was always 0.48 m/s while the number of dots forming the PLW varied between five and 12.

The flow field was a dot cloud fitted within a viewing frustum expanding 56° of visual angle in *x*-direction and 56° of visual angle in *y*-direction (106 cm × 106 cm). It consisted of 50 dots presented in random starting locations within the frustum. Previous research (Foulkes, Rushton, & Warren, 2013) showed that 50 dots provided sufficient information to minimize thresholds of heading estimates. In the experiments in which the heading speeds varied, the flow field simulated forward heading of the observer along a straight line by slowly moving the virtual camera through the scene at eight speeds of simulated heading (0.05, 0.11, 0.17, 0.23, 0.29, 0.36, 0.42, 0.48 m/s; discontinuity in the simulated heading speeds is due to rounding effects). That way, each dot appeared to move from the starting position to the end of the field of view on a linear trajectory. If a dot disappeared from view during the trial, a new dot was generated in a random starting location. Manipulating difficulty of the heading task by increasing or decreasing heading speed instead of the number of dots forming the flow field ensured that the flow field provided sufficient information about heading direction on every trial. The focus of expansion (or heading direction) was located either 5° of visual angle to the left or 5° of visual angle to the right of the center of the screen. These parameters were identified as discriminable for a group of naive participants in unpublished pilot experiments. To prevent confusion between the dots defining the PLW and the dots defining the flow field, a black patch of 22 cm height and 15 cm width (11.7° × 7.4° of visual angle) was presented behind the PLW. Dots defining the flow field appeared from behind the patch provided their starting location would have overlapped with the PLW. The points of the PLW and the flow field were white and 0.74° of visual angle in size. The flow field and PLW were rendered against a black background. The scene was present for 18 frames (300 ms). At the begin of a trial a white fixation cross rendered against a black background was shown for 200 ms followed by the scene. The intertrial interval consisted of a black screen that was shown for 200 ms.

Task

On the dual tasks, participants judged the articulation (i.e., forward or backward) of a PLW (walker task) as well as the simulated heading direction (i.e., whether they were heading to the left or the right of the PLW; heading task). For the walker task, participants responded with the right hand using the up (forward) or down (backward) arrow key. For the heading task, participants responded with the left hand using the control (left) or the alt (right) key. Participants could choose which response they entered first. On the single tasks, the stimulus was the same as for the dual tasks but only one type of motion was task-relevant and therefore only one of the two responses was required.

Procedure

We conducted two types of experiments: experiments in which the difficulty of the heading task varied and experiments in which the difficulty of the walker task varied. Table 1 shows the order in which the experiments were presented and which conditions were

Table 1
Experimental Conditions

Experiment label	Single/Dual task	Heading/Walker/Color task	Walker Type	Practice/Test	Varied difficulty
Practice session of the dual task with variation of heading difficulty	Dual	Heading Walker	Intact	Practice	Heading
Walker task with variation of heading difficulty	Single	Walker	Intact		Heading
Heading task with variation of heading difficulty	Single	Heading	Intact		Heading
Heading task (scrambled) with variation of heading difficulty	Single	Heading	Scrambled		Heading
Test session of the dual task with variation of heading difficulty	Dual	Heading Walker	Intact	Test	Heading
Dual task (color) with variation of heading difficulty	Dual	Heading Color	Scrambled		Heading
Practice session of the dual task with variation of walker difficulty	Dual	Heading Walker	Intact	Practice	Walker
Walker task with variation of walker difficulty	Single	Walker	Intact		Walker
Heading task with variation of walker difficulty	Single	Heading	Intact		Walker
Test session of the dual task with variation of walker difficulty	Dual	Heading Walker	Intact	Test	Walker
Dual task (fast heading) with variation of walker difficulty	Dual	Heading Walker	Intact		Walker

Note. Practice experiments were only included for dual tasks to test for effects of experience with the stimulus (see Koch, Poljac, Müller, & Kiesel, 2018, for a review). Single tasks were only presented once. Experiments were run in the order in which they are presented in Table 1.

presented in each experiment. Each type of experiment started with practice sessions of dual tasks (practice session of the dual task with variation of heading difficulty and practice session of the dual task with variation of walker difficulty) in which experience with the stimulus was little. Following that, single tasks were presented. Thereafter, repetitions of the dual tasks in which experience with the stimulus was high were conducted (test session of the dual task with variation of heading difficulty and test session of the dual task with variation of walker difficulty). The single task experiments were included as baseline comparisons. The practice sessions were included to test whether possible dual task effects depended on experience with the stimuli (see Koch, Poljac, Müller, & Kiesel, 2018, for a review). Furthermore, a dual task consisting of a heading task and a color discrimination task (dual task [color] with variation of heading difficulty) and a dual task with fast heading speed (dual task [fast heading] with variation of walker difficulty) were conducted. The dual task (color) with variation of heading difficulty was included to test for differences in difficulty between dual and single tasks that originated from the more complex motor response in dual tasks. The dual task (fast heading) with variation of heading performance was included to test for effects of overall task difficulty.

Just before the experiment, participants were informed about the nature of the task. A few practice trials were presented before each experiment. Conditions were presented in random order. In all but the dual task (color) with variation of heading difficulty (see below), each condition was presented five times leading to 320 trials in total. The experiments took approximately 15 min including instruction, practice trials and self-timed breaks after every block of 30 trials.

Design

Experiments with variation of heading difficulty were set up as 2 (heading direction: left, right) × 2 (articulation: forward, backward) × 2 (facing: left, right) × 8 (simulated heading speeds in m/s: 0.05, 0.11, 0.17, 0.23, 0.29, 0.36, 0.42, 0.48) within-subjects-designs leading to 64 conditions (discontinuity in the simulated heading speeds is due to rounding effects). Experiments with variation of walker difficulty were set up as 2 (heading direction: left, right) × 2 (articulation: forward, backward) × 2 (facing: left, right) × 8 (numbers of dots forming the PLW: 5, 6, 7, 8, 9, 10, 11, 12) within-subjects-designs leading to 64 conditions.

Data Analyses

We analyzed the proportion of correct responses using separate repeated-measure analyses of variance (ANOVAs) for the heading and the walker tasks. As a first step, we analyzed whether optic flow and biological motion processing interfered with one another. If optic flow and biological motion processing interfered, we would expect two main effects: (a) a main effect of heading speed on the walker task in the test session of the dual task with variation of heading difficulty and (b) a main effect of the number of dots forming the PLW on the heading task in the test session of the dual task with variation of walker difficulty. In addition, because of concurrence costs rather than interference, there could be (c) a main effect of task (worse performance on dual tasks compared to single tasks) for both the heading and the walker task. Furthermore, we tested whether ordering effects of entering the responses on dual tasks affected performances. We accepted $\alpha < .05$ as significant. When we conducted pairwise comparisons or multiple *t* tests we Bonferroni-corrected α accordingly.

To complement our repeated-measures ANOVAs, we included Bayes factor analyses to directly adjudicate between the hypothesis that performance on one task decreases with the difficulty of the other task and the hypothesis that performance on one task is independent of the difficulty of the other task. We used a one-way repeated-measures analysis with eight levels (eight heading speeds or eight numbers of dots forming the PLW) to obtain Bayes factors using the JASP software package (JASP Team, 2018). Because the Bayes factor is dependent on the prior, and we do not know the exact prior for our experimental paradigm, we performed the Bayes factor analysis with nine priors ranging from .1 to .9 to define the range of the Bayes factor. For the interpretation of the Bayes factor, we followed Wagenmakers, Wetzels, Borsboom, and van der Maas (2011) and accepted Bayes factors > 1 as indication for differences in performance for variation of task difficulty and Bayes factors < 1 as indication for consistent performance across task difficulties.

Results: Do Biological Motion and Optic Flow Processing Interfere?

Heading tasks. One-way repeated-measures ANOVAs revealed that performance on the heading tasks increased with simulated heading speed of the observer for both single—heading task with variation of heading difficulty: $F(1.63, 14.71) = 13.50$, $p = .001$, Greenhouse-Geisser corrected, $\eta_p^2 = .60$; Figure 2c—and dual tasks—test session of the dual task with variation of heading difficulty: $F(1.94, 17.50) = 13.82$, $p < .001$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.61$; Figure 2a, filled squares. We fitted cumulative Gaussian curves to the data for display purposes using the Palamedes Toolbox (Prins & Kingdom, 2018). Performance on the heading task remained constant when the number of the dots forming the PLW increased for both the single (heading task with variation of walker difficulty: $p = .98$; Figure 2f) and the dual task (test session of the dual task with variation of walker difficulty: $p = .06$, Greenhouse-Geisser corrected; Figure 2d, filled squares) which indicated independent processing of optic flow and biological motion. We therefore fitted linear regression lines to the data for display purposes. For the single heading task with variation of walker difficulty, the repeated-measures Bayes factor analysis was consistent with the repeated-measures ANOVA and indicated that performance on the heading task did not improve when the walker task was easy (the Bayes factor ranged between 0.51 and 0.01, depending on the prior setting). For heading performance during the test session of the dual task with variation in walker difficulty, however, the Bayes factor analysis indicated an increase in performance on the heading task as the walker task became easier (the Bayes factor ranged between 2.75 and 5.57, depending on the prior setting, indicating anecdotal to moderate evidence for better heading performance when the number of dots forming the PLW increased). We explored the discrepancy between the results of the repeated-measures ANOVA and the Bayes factor analysis further. As revealed by Bonferroni-corrected pairwise comparisons, the effect was driven by worse performance on the heading task when the PLW consisted of five dots compared to performance when the

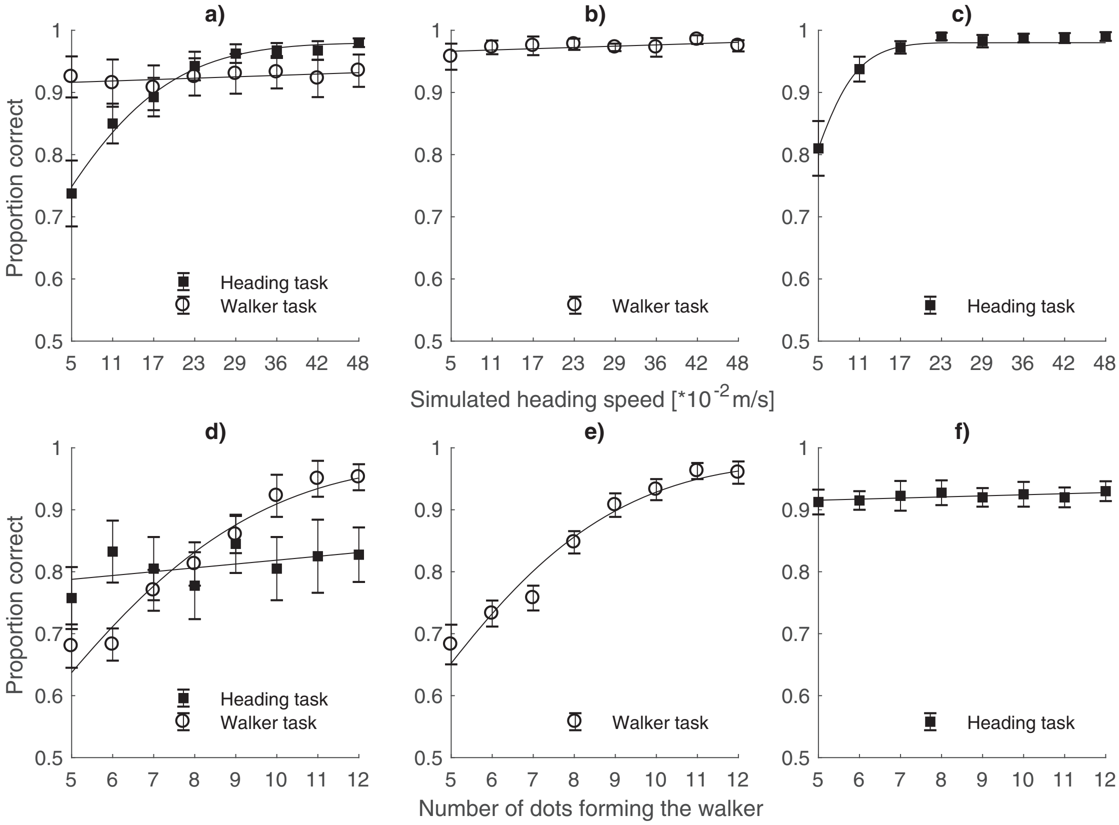

Figure 2. Proportion of correct responses as a function of simulated heading speed (top row) and the number of dots forming the point-light walker (bottom row). Open circles: proportion correct on the walker task (forward/backward articulation of a point-light walker). Filled squares: proportion correct on the heading task (leftward/rightward simulated heading of the observer). Error bars are ± 1 standard error of the means. $N = 10$. Trend lines for the varied feature (simulated heading speed in the top row; number of dots forming the point-light walker in the bottom row) are cumulative Gaussian curves; trend lines for the feature with consistent difficulty (12 dots forming the point-light walker in the top row; 0.05 m/s simulated heading speed in the bottom row) are linear regression lines. Left column: dual task performances during the test sessions. Middle column: single walker tasks. Right column: single heading tasks. Discontinuity in the x-label is due to rounding effects.

PLW consisted of 6 dots. For a PLW consisting of five dots, performance on the heading task tended to be worse at test ($M = 0.76$, $SE = 0.05$, test session of the dual task with variation of walker difficulty) than during practicing ($M = 0.80$, $SE = 0.03$, practice session of the dual task with variation of walker difficulty) which suggested underachievement at the test session. Furthermore, the linear regression line fitted to the heading performance across the number of dots forming the PLW had a slope close to zero (0.0062), which indicated that the performance did not improve when the walker task was easy. The result of the repeated-measures ANOVA and the Bayes factor analysis point toward unsystematic variations in performance and might not reflect a reliable effect. Thus, these results indicated that heading performance did not depend on difficulty of the walker task. Furthermore, Bonferroni-corrected paired samples *t* tests revealed that dual task performance was worse than single task performance for both variation of heading difficulty, $t(9) = 3.60$, $p = .01$; dual task: $M = 0.91$, $SE = .02$; single task: $M = 0.96$, $SE = 0.01$ and variation of walker difficulty, $t(9) = 2.81$, $p = .02$; dual task: $M = 0.81$, $SE = 0.05$; single task: $M = 0.92$, $SE = 0.02$.

As a next step, we tested whether performance on the heading task depended on the number of dots forming the PLW after correcting for the difference between single and dual task performance. We calculated the difference between single and dual task performance for each number of dots forming the PLW and each participant separately (dual task performance–single task performance) and added the difference to each participant's dual task performance for each number of dots forming the PLW. The results remained qualitatively the same as for the uncorrected performances: there was no main effect of the number of dots forming the PLW on heading task performance, $F(7, 63) = 2.63$, $p = .082$, Greenhouse-Geisser corrected, $\eta_p^2 = 0.23$; the Bayes factor ranged between 1.25 and 3.14, depending on the prior setting. There were no biases with respect to the perceived heading direction depending on the PLW's facing or articulation direction. A 2 (heading direction: left, right) × 2 (facing: left, right) × 2 (articulation: forward, backward) × 8 (simulated heading speeds in m/s: 0.05, 0.11, 0.17, 0.23, 0.29, 0.36, 0.42, 0.48; discontinuity in the simulated heading speeds is due to rounding effects) repeated-measures ANOVA showed no significant interactions ($ps > .29$).

Walker tasks. One-way repeated-measures ANOVAs revealed that performance on the walker task increased with the number of dots forming the PLW for both single—walker task with variation of walker difficulty: $F(2.86, 25.78) = 58.31$, $p < .001$, Greenhouse-Geisser corrected, $\eta_p^2 = .87$; Figure 2e—and dual tasks—test session of the dual task with variation of walker difficulty: $F(7, 63) = 51.08$, $p < .001$, $\eta_p^2 = .85$; Figure 2d, open circles. We fitted cumulative Gaussian curves to the data for display purposes using the Palamedes Toolbox (Prins & Kingdom, 2018). When increasing the simulated heading speed performance on the walker task remained constant for single (walker task with variation of heading difficulty: $p = .54$, Greenhouse-Geisser corrected; Figure 2b) and dual tasks (test session of the dual task with variation of heading difficulty: $p = .63$; Figure 2a, open circles). We, therefore, fitted linear regression lines to the data for display purposes. This finding indicated that performance on the walker task was independent of the difficulty of the heading task. The Bayes factor of a one-way repeated-measures analysis was in line with the repeated-measures ANOVA indicating that performance on the walker task did not depend on difficulty of the heading task (walker task with variation in heading difficulty: Bayes factor ranged between 0.02 and 0.64, depending on the prior setting; test session of the dual task with variation in heading difficulty: Bayes factor ranged between 0.02 and 0.64, depending on the prior setting). Performance on the walker tasks was consistent for dual and single tasks (paired samples *t* tests, variation of heading difficulty: $p = .05$; variation of walker difficulty: $p = .28$; Bonferroni-corrected).

Are There Differences in Performance Due to the Ordering of the Responses?

Participants were free to choose whether they entered the response for the heading task or the response for the walker task first. This could have potentially led to participants developing response strategies (e.g., always responding to the heading task second) that might have biased the pattern of accuracies. It is possible, for example, that responding second to the heading task leads to worse performance due to memory effects.

Data Analyses

First, we tested for individual response strategies in the test session of the dual task with variation in heading difficulty and the test session of the dual task with variation of walker difficulty. Four of the participants predominantly entered the response for the heading task first and five participants predominantly entered the response for the walker task first. One participant changed the strategy frequently throughout the experiments. All participants used the same strategy across test sessions with variation of heading difficulty and walker difficulty. The proportions of first heading responses are shown in Table 2. To analyze whether the response strategies led to systematic biases in the pattern of accuracies we calculated paired-samples *t* tests for the proportion of incorrect first responses and incorrect second responses for the test sessions of the dual tasks.

Table 2
Proportion of First Heading Responses

Participant	Test session of the dual task with variation of heading difficulty	Test session of the dual task with variation of walker difficulty
1	.1031	.0406
2	1	.9969
3	.0031	.0031
4	1	.9938
5	.375	.2031
6	1	.9969
7	0	0
8	0	.0219
9	0	0
10	1	1

Results

Bonferroni-corrected paired samples *t* tests revealed that the proportion of incorrect responses did not differ based on the ordering of the responses for both the heading and the walker tasks (test session of the dual task with variation of heading difficulty: heading task: $p = .68$, walker task: $p = .19$; test session of the dual task with variation of walker difficulty: heading task: $p = .12$, walker task: $p = .68$).

Discussion

The pattern of responses on the walker and heading tasks showed that varying the difficulty of one task did not affect performance on the other. These results indicated that the heading and the walker task were processed independently by the visual system. For the biological motion task, dual task performance was at the same performance level as single task performance. For the heading task, dual task performance was worse than single task performance. The decline in performance may have originated from concurrence costs. Concurrence costs occur because the process of coordinating two tasks requires resources itself and can lead to a decrease in performance (Gopher & Navon, 1980; Wickens, Hollands, Banbury, & Parasuraman, 2015). In informal conversations between the participants and the experimenter, participants reported that they found the heading task difficult despite their above-chance performances. Heading performance might be more vulnerable to concurrence costs than performance on the walker task due to the subjectively experienced overall difficulty of the heading task. It is unlikely that the concurrence cost originated from the specific task design used in our experiments. There were no systematic effects on the error rates depending on the ordering of the key presses when responding to the two motion tasks on the dual task experiments. We, therefore, assume that working memory effects had no critical effect on the pattern of results. In the following sections, we test for potential sources of the concurrence cost found for heading performance, such as practice effects, incidental processing of biological motion, effects of more complex motor responses on dual tasks compared to single tasks and overall task difficulty.

Can the Concurrence Cost Be Explained by Lack of Practice?

Worse heading performance on dual tasks might have originated from participants not being sufficiently experienced with the stimuli. Several studies (see Koch et al., 2018, for a review) showed that practice can reduce or even eliminate dual task effects. Therefore, as a next step, we tested for differences in performances between practice sessions and test sessions of the dual tasks. We compared dual task performance when participants were experienced with the stimulus (test) to dual task performance when participants had little experience with the stimulus (practice).

Separate 2 (level: practice, test) × 8 (simulated heading speed or number of dots forming the PLW) repeated-measures ANOVAs revealed no main effects of level or interactions for both the heading (variation of heading difficulty: main effect of level: $p = .10$, main effect of simulated heading speed: $p < .001$, Greenhouse-Geisser corrected, interaction: $p = .69$, Greenhouse-Geisser corrected; variation of walker difficulty: main effect of level: $p = .87$, main effect of the number of dots forming the PLW: $p = .12$, interaction: $p = .31$, Greenhouse-Geisser corrected) and the walker task (variation of heading difficulty: main effect of level: $p = .23$, main effect of simulated heading speed: $p = .79$, Greenhouse-Geisser corrected, interaction: $p = .53$; variation of walker difficulty: main effect of level: $p = .06$, main effect of the number of dots forming the PLW: $p < .001$, interaction: $p = .72$) and both variation of heading difficulty and variation of walker difficulty. The results are presented in Figures 3a and 3d. As for test sessions, we fitted cumulative Gaussian curves to the data of the task of which we varied the difficulty and linear regression lines to the data of the task with the constant difficulty for display purposes.

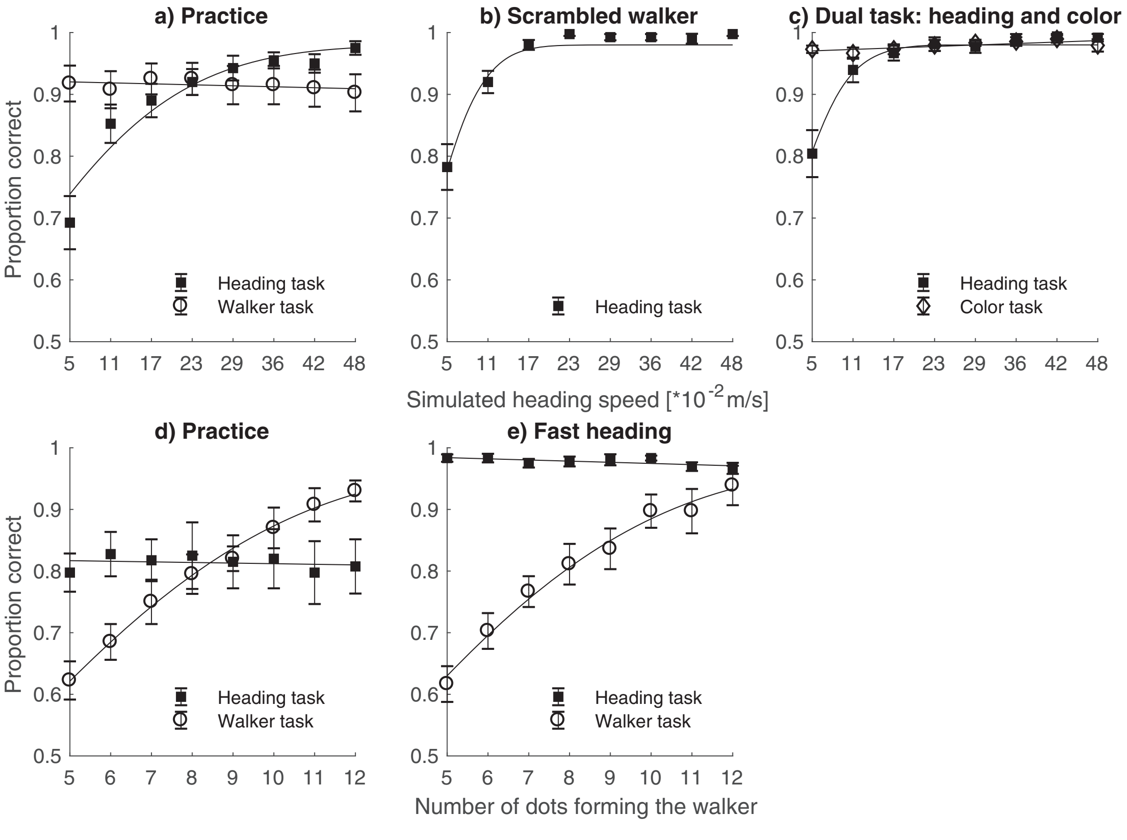

Figure 3. Results of the experiments investigating the concurrence cost found for heading performance. Open circles: proportion correct in the walker task (forward/backward articulation of a point-light walker). Filled squares: proportion correct in the heading task (leftward/rightward simulated heading of the observer). Open diamonds: proportion correct in the color discrimination task. Trend lines are linear regression lines for tasks with consistent difficulty and cumulative Gaussian curves for tasks in which difficulty was varied. Error bars are ± 1 standard error of the means. Discontinuity in the x-label is due to rounding effects. A–D: $N = 10$. E: $N = 9$. A: Proportion correct in the practice session of the dual task with variation of heading difficulty (the point-light walker consisted of 12 dots). B: Proportion correct in the heading task (scrambled) with variation of heading difficulty. C: Proportion correct in the dual task (color) with variation of heading difficulty. D: Proportion correct in the practice session of the dual task with variation in walker difficulty (simulated heading speed was 0.05 m/s). E: Proportion correct in the dual task (fast heading) with variation of walker difficulty (simulated heading speed was 0.48 m/s).

Overall, the results indicated that concurrence costs found for the heading task cannot be explained by insufficient familiarity with the stimulus and the particular dual task design used in our experiments.

Can Incidental Processing of Biological Motion Explain the Concurrence Cost?

Another potential explanation for worse heading performance on dual compared to single tasks are attentional processes. Both human shape and motion have been found to be highly salient (Beintema & Lappe, 2002; Cavanagh et al., 2001; Troje & Westhoff, 2006). Furthermore, it was found that the human body can capture attention (Downing et al., 2004) and that task-irrelevant biological motion interferes with direction and motion discrimination tasks (Fujimoto & Yagi, 2008; Thornton & Vuong, 2004). It might therefore be that the PLW in our stimuli captured attention and limited the attentional resources necessary for processing optic flow even when the PLW was task-irrelevant (heading task with variation of heading difficulty). We therefore tested for possible attentional effects caused by biological motion processing. We conducted a single task paradigm with a heading task but replaced the PLW with a task-irrelevant scrambled PLW. Spatially scrambled PLWs are created by randomizing the position of each dot of the PLW, which serves to disrupt the underlying form of a walker. Consequently, the processing of biological motion is impaired for scrambled PLWs (e.g., Beintema & Lappe, 2002; Troje & Westhoff, 2006). The scrambling process can effectively reduce influences of biological motion (Fujimoto & Yagi, 2008; Thornton & Vuong, 2004).

Method

The scene in the heading task (scrambled) with variation of heading difficulty differed from the heading task with variation of heading difficulty with respect to the PLW. Instead of a PLW, a spatially scrambled version of the PLW was presented. This means that the spatial positions of the dots within the black patch behind the PLW were randomized but the motion trajectory of each dot remained the same. The same scrambled PLW was used throughout the experiment. The procedure, task and design were identical to the heading task with variation of heading difficulty.

Results and Discussion

We compared single task performances for a task-irrelevant intact (heading task with variation of heading difficulty) and a task-irrelevant scrambled PLW (heading task [scrambled] with variation of heading difficulty). A 2 (walker: intact, scrambled) × 8 (simulated heading speeds in m/s: 0.05, 0.11, 0.17, 0.23, 0.29, 0.36, 0.42, 0.48) repeated-measures ANOVA showed that the main effect of walker ($p = .93$) and the interaction of walker and simulated heading speed were not significant ($p = .46$, Greenhouse-Geisser corrected). There was a main effect of simulated heading speed, $F(1.43, 12.84) = 25.05$, $p < .001$, Greenhouse-Geisser corrected, $\eta_p^2 = .74$, indicating that performance improved with simulated heading speed. The results are presented in Figure 3b. Single task performances on the heading tasks did not differ depending on whether a task-irrelevant PLW or scrambled PLW was present in the scene. Given these results, we suggest that the concurrence cost found in the test session of the dual task with variation of heading difficulty is unlikely to be due to attentional processes that allocated more resources to the walker task than the heading task. In contrast to previous findings (Fujimoto & Yagi, 2008; Thornton & Vuong, 2004), we did not find evidence for incidental processing of the walker. This may be because of the different experimental paradigms used in the present and the previous experiments. None of the previous studies combined a biological motion and a heading task. Alternatively, it may be that the heading task did not require attentional resources. This, however, is an unlikely explanation in the context of previous work. Royden and Hildreth (1999) found that heading judgments were attentionally demanding in a dual task design. The lack of evidence for incidental processing or attention capturing of the PLW in the heading task with variation of heading difficulty indicated that participants were able to perform the optic flow task independently of the biological motion task.

Can a More Difficult Motor Response Explain the Concurrence Cost?

Another potential explanation for the worse heading performance on dual tasks than single tasks found in the test sessions might be general difficulties with our paradigm such as the response collection (e.g., translating the responses into key presses). Concurrence costs of heading performance may have occurred due to motion-unspecific factors such as translating two responses into button presses in dual tasks compared to only one response in single tasks. As participants reported that they found the heading task difficult, it may be that the heading task was more vulnerable to concurrence costs because of the task design rather than the walker task. To test for concurrence costs due to the task design, we conducted a dual task in which the biological motion task was replaced by a color discrimination task. The heading task and the response collection were the same as in the test sessions. If the concurrence cost was due to motion-unspecific effects, we would expect worse heading performance in the dual task (color) with variation of heading difficulty than in the single heading tasks (heading task with variation of heading difficulty and heading task [scrambled] with variation of heading difficulty).

Design

The factor color with two levels (red, green) was added to the design of the dual task with variation of heading difficulty leading to a 2 (heading direction: left, right) × 2 (articulation: forward, backward) × 2 (facing: left, right) × 8 (simulated heading speeds in m/s: 0.05, 0.11, 0.17, 0.23, 0.29, 0.36, 0.42, 0.48) × 2 (color: red, green) within-subjects-designs with 128 conditions (discontinuity in the simulated heading speeds is due to rounding effects).

Method

Stimuli. The same scene as in the heading task (scrambled) with variation of heading difficulty was used except that the dots forming the scrambled PLW were green on half of the trials and red on the other half of the trials.

Task. Participants performed the same heading task as in the dual task with variation of heading difficulty. In addition, they pressed the up arrow key when the scrambled PLW consisted of green dots and the down arrow key when the scrambled PLW consisted of red dots. As in the dual task with variation of heading difficulty, participants could choose which response they entered first.

Procedure. To keep the duration of the experiment approximately similar to the other experiments every condition was presented three times, thus, there were 384 trials in total. The total duration of the experiment was approximately 20 min including instruction, practice trials and self-timed breaks after every block of 30 trials.

Results

Heading task. A 4 (experiment: test session of the dual task with variation of heading difficulty, dual task [color] with variation of heading difficulty, heading task with variation of heading difficulty, heading task [scrambled] with variation of heading difficulty) × 8 (simulated heading speeds in m/s: 0.05, 0.11, 0.17, 0.23, 0.29, 0.36, 0.42, 0.48) repeated-measures ANOVA showed a main effect of experiment, $F(1.15, 10.36) = 8.84$, $p = .01$, Greenhouse-Geisser corrected, $\eta_p^2 = .50$ (Bonferroni-corrected pairwise comparisons revealed worse performance in the test session of the dual task with variation of heading difficulty compared to any other experiment), and a main effect of simulated heading speed, $F(1.80, 16.22) = 44.02$, $p < .001$, Greenhouse-Geisser corrected, $\eta_p^2 = .83$, indicating that performance improved with simulated heading speed. The interaction of simulated heading speed and experiment was also significant, $F(21, 189) = 3.22$, $p < .001$, $\eta_p^2 = .26$. The results are presented in Figure 3c (filled squares).

Color task. A one-way repeated-measures ANOVA revealed no main effect of simulated heading speed for color discrimination performance ($p = .19$; Figure 3c, open diamonds). This finding indicated that color discrimination performance was independent of the difficulty of the heading task. The Bayes factor analysis was consistent. The Bayes factor ranged between 0.11 and 0.98, depending on the prior setting.

Discussion

There was no evidence for dual task interference or concurrence costs when a heading and a color task were performed concurrently. Heading performance in the dual task (color) with variation of heading difficulty did not differ from the performances on single heading tasks (heading task with variation of heading difficulty and heading task [scrambled] with variation of heading difficulty). On the color discrimination task performance was high (proportion correct $> .96$ across different simulated heading speeds). The high proportion of correct responses was achieved even though the mapping between the colors and the keys (green: up arrow key; red: down arrow key) was arbitrary. In informal conversations with the experimenter, participants reported that they found the mapping of the dual task (color) with variation of heading difficulty less intuitive than in the remaining the experiments. This indicated that the process of translating responses into motor output was harder in the dual task (color) with variation of heading difficulty than in the previous dual tasks. The lack of concurrence costs when a heading task and a color discrimination task were performed were at odds with the explanation that reduced performance on dual tasks compared to single tasks resulted from the specific response paradigm used in the test sessions of the previous dual task experiments. Overall task difficulty might have played a role as to why we found concurrence costs in dual tasks with heading and walker tasks (test session of the dual task with variation of heading difficulty and test session of the dual task with variation of walker difficulty) but not in the dual task with heading and color tasks (dual task [color] with variation of heading difficulty). The color task differed from the walker task in two respects. First, color could, in principal, be extracted on the basis of a single frame from the animation. Furthermore, the colors were clearly discriminable. In the walker task, however, information about limb posture needed to be accumulated across several frames to correctly judge articulation (Theusner et al., 2014). Second, the walker and the color tasks also differed with respect to the attentional demands. Previous research (Mayer & Vuong, 2012) found that object color is learned during a familiarization phase with novel objects even when attention is intentionally guided to other features such as shape and motion. This indicated that color processing might require little attention during processing of complex dynamic objects consistent with the concept of color as a preattentive feature (Treisman, 1982). Both the walker and the heading task, by comparison, have been shown to be attentionally demanding (Royden & Hildreth, 1999; Thornton et al., 2002).

In summary, the lack of concurrence costs and dual task interference for the heading and the color task showed that worse heading performances on dual compared to single tasks did not originate from the required motor responses. Furthermore, the results of the dual task (color) with variation of heading difficulty corroborated the hypothesis that worse dual task performance compared to single task performance in the previous experiments was due to a concurrence cost as the color task was easier than the walker task and therefore may not have required resources to coordinate the two tasks.

Can Difficulty of the Heading Task Explain the Concurrence Cost?

The concurrence cost was found for the heading but not the walker task. This asymmetry might have originated from overall differences in difficulty between the dual task with variation in heading difficulty and the dual task with variation in walker difficulty. In the dual task experiments in which we varied the number of dots forming the PLW we presented a difficult heading task (heading speed was 0.05 m/s) whereas in the experiments in which we varied simulated heading speeds we presented an easy walker task (12 dots forming the PLW). To test for influences of overall task difficulty on the concurrence cost, we conducted a further dual task experiment with variation in walker difficulty. This time, however, we used a heading speed of 0.48 m/s.

Method

The methods were identical to the dual task with variation in walker difficulty except that heading speed was 0.48 m/s. Nine out of the 10 participants tested in the other experiments took part.

Results and Discussion

Heading task. A one-way repeated-measures ANOVA revealed no main effect of the number of dots forming the PLW (p = .313). This indicated that the difficulty of the walker task had no effect on heading performance. The results of the Bayes factor analysis were consistent. The Bayes factor ranged between 0.07 and 0.84, depending on the prior setting. There was no indication for a concurrence cost (dual task [fast heading] with variation in walker difficulty: $M = .98$, $SE = .004$; heading task with variation in walker difficulty: $M = .91$, $SE = .01$). Hence, no concurrence cost was observed when the heading task was comparatively easy. The results are presented in Figure 3e (filled squares).

Walker task. A one-way repeated-measures ANOVA revealed a main effect of the number of dots forming the PLW, $F(7, 56) = 32.12$, $p < .001$, $\eta_p^2 = .89$, indicating that performance improved with the number of dots forming the PLW. The results are presented in Figure 3e (open circles).

The concurrence cost found for the heading tasks disappeared for fast heading. The results indicate that the concurrence cost found in the dual task with variation in walker difficulty was at least partly due to the overall difficulty of the task rather than interference between optic flow and biological motion processing. In summary, the results suggest that the concurrence cost can be reduced if the heading task is easy.

General Discussion

Processing optic flow and biological motion concurrently is a common challenge for the visual system in natural environments. We used dual task paradigms to investigate whether concurrent processing of the two types of motion leads to interference. Our results indicated that there was no interference which corroborates the hypothesis of independent processing of biological motion and optic flow as derived from neuroimaging (e.g., Grossman et al., 2000; Peuskens et al., 2001) and conceptual studies (Beintema & Lappe, 2002; Lange & Lappe, 2006; Lappe & Rauschecker, 1993; Theusner et al., 2014). For optic flow processing, however, we found worse performance for dual than for single tasks when the heading task was difficult. We suggest that this was due to a concurrence cost (Gopher & Navon, 1980).

Interferences between two concurrently performed tasks indicate that a shared resource with limited capacity is required to perform the tasks (e.g., Norman & Bobrow, 1975). Such shared resources can occur at various levels during visual processing (Franconeri et al., 2013; Pashler, 1994; see Marois & Ivanoff, 2005, for a review). In particular, shared resources can be inferred from dual task paradigms when increased difficulty of one task leads to a decrease in performance on the other task or when allocating attention predominantly to one task leads to a decrease in performance on the other task (Norman & Bobrow, 1975). Furthermore, interference is usually accompanied by worse performance on dual tasks than on single tasks (Norman & Bobrow, 1975). In the present study, increased difficulty of either task did not produce performance change in the other. Our results indicate independent processing of optic flow and biological motion.

At the neural level, independent processing of optic flow and biological motion can be inferred from neuroimaging studies and formal models that describe computational procedures of the neurons. Tasks that elicit responses in distinct brain areas are less likely to interfere during concurrent performance than tasks that elicit responses in overlapping brain areas (Alavash et al., 2015; Nijboer et al., 2016). Neuroimaging studies have found largely segregated brain areas specialized in processing optic flow (see Greenlee, 2000, for a review) and biological motion (e.g., Grossman et al., 2000). At a conceptual level, formal models that describe how optic flow and biological motion are processed developed fundamentally different approaches for the two types of motion. The models that describe how biological stimuli are processed rely on the integration of prior knowledge about the shape and kinematics of the human body with bottom-up visual features (Beintema & Lappe, 2002; Lange & Lappe, 2006; Theusner et al., 2014). By comparison, models that describe how optic flow is used for heading estimation rely on the particular motion of objects that are stationary in the environment across the retinae when the observer moves (Lappe & Rauschecker, 1993; Longuet-Higgins & Prazdny, 1980; Perrone & Stone, 1994; see Raudies & Neumann, 2012, for a review). Such diverging approaches imply that different populations of neurons might be involved in processing the two types of motion. In the context of the neuroimaging studies and the formal models, the results of the present study complement the existing understanding of how the brain processes optic flow and biological motion. The present study provides evidence at the behavioral level that is consistent with the idea that the visual system implements different mechanisms for processing these two types of motion. Directly comparing performances during concurrent and separate processing of optic flow and biological motion thus corroborates existing knowledge on how the brain achieves everyday life challenges such as navigating in the presence of other people.

When multiple types of motion are perceived concurrently, processes for segmentation of the different motions might be enabled. In our stimulus, the PLW was separated from the flow field by an area of 11.7° × 7.4° of visual angle in which no flow dots were presented. This provided a clear segmentation of the PLW from the flow field. Segmentation of independent motion during heading estimation might also be supported by the motion-based cues accretion/deletion, acceleration/deceleration, expansion/contraction, and spatial and temporal curvature (Raudies & Neumann, 2013). However, Li, Ni, Lappe, Niehorster, and Sun (2018) recently showed that human observers do not use segmentation of independently moving objects for heading estimation. It is therefore possible that—although segmentation cues were available in our study—observers did not use them for estimating heading direction in the presence of a PLW.

When comparing dual and single task performance we found that the performance on the heading tasks was worse on dual tasks than on single tasks when the heading task was comparably difficult. Worse dual task performance with respect to single task performance, however, is not sufficient to infer shared resources (Norman & Bobrow, 1975). Shared resources are likely when—in addition to worse dual task performance—performance on one task is dependent on the difficulty of the other task (Norman & Bobrow, 1975). Alternatively, shared resources are likely when varying the amount of attention allocated to one task affects performance on the other task (e.g., Royden & Hildreth, 1999). An isolated decline in performance on dual tasks compared to single tasks that is not affected by attentional allocation or difficulty of the other task is termed a concurrence cost (Gopher & Navon, 1980). That is, the decline in performance may be due to resources being allocated to coordinating the performance of two tasks rather than the two tasks actually interfering. Generally, observers reported that they found the heading task extremely difficult even during single tasks which could have led to subjective uncertainty. It may therefore be that the heading task was vulnerable to concurrence costs. In line with this suggestion the concurrence cost disappeared in the dual task experiment when the heading task was easy.

Previous research found general biases in heading estimation in the presence of independently moving objects (Andersen & Saidpour, 2002; Kim, 2000; Layton, Mingolla, & Browning, 2012; Li et al., 2018; Royden & Hildreth, 1996; Warren & Saunders, 1995). A PLW introduces independent motion to the optic flow just like the moving objects in the previous studies. In these studies, human observers were presented with optic flow fields in which simple geometric objects that moved were placed. Warren and Saunders (1995) found that an independently moving object that occluded the focus of expansion of the flow field biased the perceived direction of the simulated heading. The bias depended on properties of the object such as whether its surface was transparent or opaque. Royden and Hildreth (1996) found that heading judgments were biased toward an independently moving object in cases when the object crossed the simulated heading path of the observer. The present study did not find evidence for biases in heading estimates in the presence of a PLW. The stimulus used in the present study differed substantially from the ones previously used. The objects in previous studies moved by translating in space (e.g., Royden & Hildreth, 1996; Warren & Saunders, 1995), whereas our PLW was fixed in space but articulated causing nonrigid motion. As the overall movement from the articulation is balanced it may best be regarded as additional noise to the flow field (cf. Riddell & Lappe, 2018). Furthermore, we ensured that the focus of expansion was not occluded. We therefore suggest that the concurrence cost found in the present study was due to overall difficulty of the heading task rather than biases in the heading estimates caused by the presence of an independently moving object. Future research is needed to directly investigate whether a translating PLW causes biases in the heading estimates as previously found for geometric objects.

We did not find concurrence costs or dual task interference on the walker tasks. This finding is consistent with independent processing of biological motion and optic flow. Because of the high sensitivity of the visual system to biological stimuli (Cavanagh et al., 2001; Downing et al., 2004; Mayer et al., 2015, 2017; Thornton & Vuong, 2004; Troje & Westhoff, 2006) it may be that the PLW captured attention and therefore comprised performance on the heading task. This explanation is unlikely, however. Although previous studies reported that the human body captured attention (Downing et al., 2004), attracted eye movements (Bindemann et al., 2010; Mayer et al., 2015, 2017), and was processed incidentally (Thornton & Vuong, 2004), we did not find evidence for such preferential processing of biological motion. Replacing a task-irrelevant PLW with a scrambled PLW did not improve performance on the heading task. This finding argued against impaired performance on the heading task due to preferential processing of biological motion. Results of further analyses and control experiments that tested for ordering of the key presses when responding, practice effects (see Koch et al., 2018, for a review), and differences in the difficulties of the motor responses of dual and single tasks (Pashler, 1994) suggested that the decrease in performance did not originate from these sources. As reported above, we therefore suggest that the decrease in performance only occurred for the heading task because observers found the heading task difficult which led to uncertainty and made the heading task vulnerable for concurrence costs. In line with this suggestion, the concurrence cost disappeared when the heading task was easy.

Previous studies (Royden & Hildreth, 1999; Thornton et al., 2002) found that performing optic flow and biological motion tasks concurrently with other visual tasks led to decreased performance. With respect to biological motion processing, Thornton et al. (2002) showed that adding a dual task that was attentionally demanding led to decreases in performance of left/right articulation judgments. Although our PLW was similar to the one used by Thornton et al. (2002) and both studies used tasks that involved judging articulation of a PLW, we did not find evidence for dual task interference. It may be that the heading task used in the present study was attentionally less demanding than the change-discrimination task used in Thornton et al.'s (2002) study. This, however, is unlikely. As reported above, observers in our study found the heading task difficult. This implied that participants may have allocated substantial attentional resources to the heading task to discriminate heading direction. Based on the overall pattern of our results it is more likely that separate resources were involved in processing the two types of motion in the present study whereas shared resources were involved in Thornton et al.'s (2002) study.

In their dual task paradigm, Royden and Hildreth (1999) found dual task interference when a heading task was combined with an object tracking task. Though difficult to compare because of different task designs and stimuli, our findings might reconcile with the findings by Royden and Hildreth (1999). They found that performance on a heading task declined when a concurrent object tracking task was presented. There was, however, no additional decline when attention was predominantly allocated to the object tracking task. This is in line with our findings. In the present study, adding a biological motion task decreased performance on a difficult heading task but it did not decrease further with increased difficulty of the walker task. Taken together, Royden and Hildreth's (1999) findings and the present study suggest that although heading performance is subject to decreases in performance such as concurrence costs, it is robust to attentional shifts and changes of difficulties in concurrent tasks. This could be seen as converging evidence that heading is a mechanism largely independent of the processing of other types of motion. Moreover, when our heading task was performed concurrently with a task that had little attentional demands (i.e., the color task in the dual task [color] with variation of heading difficulty) or when the heading task was easy (i.e., the heading task in the dual task [fast heading] with variation of walker difficulty) there was no evidence for concurrence costs. Comparing the findings of dual task paradigms of the previous studies (Royden & Hildreth, 1999; Thornton et al., 2002) to the present study showed that dual tasks involving optic flow or biological motion do not lead to interferences per se, but that the specific combination of visual tasks is critical as to whether dual task interference occurs. This comparison further supports the concept of independent processing of optic flow and biological motion found in the present study.

In summary, the present results suggested that the visual system is capable of independent processing of biological motion and optic flow. Both types of motion are important aspects of visual perception, as they allow us to remain spatially oriented (Cutting et al., 1992; Gibson, 1950; Lappe et al., 1999) and to accurately judge the motion of others (Johansson, 1973). Lack of interference between them is highly adaptive as it is critical for many situations in everyday life to perform both tasks concurrently such as driving, playing sports or navigating through crowded streets.

Conclusion

The present study found no evidence for interferences between optic flow and biological motion when both types of motion were processed concurrently. Thus, our results are in line with a concept of independent resources within the visual system that process optic flow and biological motion. Our results corroborate formal models that describe fundamentally different computational efforts of neurons when processing the two types of motion.

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