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Kinematic cues for person identification from biological motion

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We examined the role of kinematic information for person identification. Observers learned to name seven walkers shown as point-light displays that were normalized by their size, shape, and gait frequency under a frontal, half-profile, or profile view. In two experiments, we analyzed the impact of individual harmonics as created by a Fourier analysis of a walking pattern, as well as the relative importance of the amplitude and the phase spectra in walkers shown from different viewpoints. The first harmonic contained most of the individual information, but performance was also above chance level when only the second harmonic was available. Normalization of the amplitude of a walking pattern resulted in a severe deterioration of performance, whereas the relative phase of the point lights was only used from a frontal viewpoint. No overall advantage for a single learning viewpoint was found, and there is considerable generalization to novel testing viewpoints.

When Swedish psychologist Gunnar Johansson advanced a new method to filter motion information from point-light displays (PLDs) of human walkers some 30 years ago (Johansson, 1973, 1976), he stimulated a great variety of research on this topic. Johansson attached retroreflective tape to his models that reflected the light of external sources at their major joints, and he used specific video adjustments to separate the movements of the joints from all other visual information about the person. Observers were able to immediately recognize the structure of the human body underlying the movements of the point lights. A display time of 500 msec was sufficient to discriminate a variety of motion patterns. Researchers soon focused on issues such as the identification of the gender of a person (Barclay, Cutting, & Kozlowski, 1978; Kozlowski & Cutting, 1977; Mather & Murdoch, 1994; Troje, 2002a, 2002b), his or her identity (Cutting & Kozlowski, 1977; Loula, Prasad, Harber, & Shiffrar, 2005; Stevenage, Nixon, & Vince, 1999; Troje, Westhoff, & Lavrov, 2005), or the type of movements they performed (Dittrich, 1993).

Cutting and Kozlowski (1977) showed that the motion of point lights is sufficient for recognition within a group of friends. Stimuli were generated using Johansson's (1973, 1976) video technique. The authors recorded the gait patterns of six walkers who were moving on the screen in the sagittal plane. Starting with a low performance, observers reached a level of correct identifications at the end of the experiment that was high above chance performance, even though they did not get feedback about their answers. When asked about what cues they had used to identify the walkers, observers mentioned characteristics such as speed, rhythm, amount of arm swing, length of steps, and others.

Stevenage et al. (1999) videotaped six walkers whose identifying characteristics such as face, hair, or detailed body shape were masked under different display conditions (daylight, dusk, PLD). Female walkers could be identified more easily than male walkers by naive observers, but neither the gender of the perceiver nor the display condition had a significant effect on identification performance. The latter finding was counted as strong evidence that observers used gait-related rather than body-related cues to solve the identification task, because the different amounts of information about general shape in the different display conditions apparently had no effect on recognition performance.

How does the visual system accomplish the task of acquiring information about shape and motion from degraded displays? In a study dealing with dynamic face perception, Pittenger and Shaw (1975) first noted that the perception of any event has two components. One component is the detection of "structural invariants"—that is, invariant information specifying the structure to which movement is applied. As long as PLDs remain static, revealing the articulation of the body and its general struc-

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ture is a complicated task and riddled with ambiguities. However, as soon as the displays start to move in a coherent fashion, the structure of the object becomes apparent. Troje (2002a) called this *motion-mediated structural information*.

However, the kinematics of the moving point lights reveals more than just the structure of the body. Pittenger and Shaw (1975) called these nonstructural components *transformational invariants*. Runeson and Frykholm (1981, 1983) focused on the fact that observers are able to derive the underlying dynamics (masses, forces, momentum, etc.) of an action from kinematic cues. For example, observers in their experiments could estimate the weight of a lifted box or how far a sandbag was thrown. Assuming that visual kinematics provides a representation of the underlying dynamics of an event, observers should be able to recognize individual persons over a variety of motion patterns, because the anatomical proportions of the body and the distribution of its masses constrain the way in which the person moves. If we focus on the motion patterns of individual persons, one of the most often performed and thus most characteristic patterns is walking.

Using discrete marker trajectories derived by means of a motion capture system, Troje (2002a) proposed a method to decompose human walking data into structural and kinematic information and to isolate the main sources of kinematic variance. The structure of a walker was defined simply as the mean posture of a walker derived by averaging the Cartesian coordinates of the markers over several walking cycles. Subtracting the average posture, the remaining kinematic data were then subjected to a principal components analysis (PCA). It turned out that for a single walker, four principal components were sufficient to recover more than 98% of the overall variance in postural space. Looking at the sinusoidal time course of the loads of the principal postures, it became obvious that PCA basically decomposed the time series of postures into a discrete Fourier expansion (Troje, 2002b). The fact that PCA and Fourier analysis result in virtually the same decomposition means that Fourier analysis is optimal in terms of recovering and explaining variance in the data. We therefore adopted this decomposition for our current investigations on which parts of the kinematic information are relevant for person identification.

The perceptual significance of structural and kinematic properties of PLDs was subject to several studies. Mather and Murdoch (1994) examined whether observers relied more on structural or on kinematic cues to identify the gender of a point-light walker. They synthesized different types of walkers by distinguishing male or female shoulder-to-hip ratio as a structural cue and lateral movements of the upper body as a kinematic cue. By combining these two factors, the authors created different types of walkers with corresponding or contradicting information about the walker's gender. They showed that observers relied more on the kinematic cue than on the structural cue, but only if the walkers were shown from a frontal view and not from a half-profile view. The latter resulted in very poor gender identification, although much of the relevant information was still accessible. It seemed that in the half-profile view, there was no cue in the displays that helped the subjects to decide between a male or female walker. The findings about structural and kinematic cues contradict earlier results of Barclay et al. (1978), who suggested that torso shape is a cue for gender identification. These authors found that observers detected gender by analyzing the center-of-moment of the upper body, which in turn is determined by the shoulder-to-hip ratio.

Using motion capture data from 40 walkers, Troje (2002a) synthesized PLDs by replacing individual kinematic or structural information of the walkers by the mean values of the database. These stimuli were shown to observers who had to classify the gender of the walkers from three different viewing angles (frontal, half-profile, or profile view). Gender classification was best in the frontal view and worst in the profile view. The results also confirmed a predominant role of dynamic information. However, in contrast to the data of Mather and Murdoch (1994), the lack of diagnostic dynamic information was most hindering in the profile-view condition and had less of an impact in the frontal-view condition.

Troje et al. (2005) examined the relevance of structural and kinematic information under varying viewpoints in an identification task. The authors used the methods proposed by Troje (2002a, 2002b) to create PLDs of walkers with different kinds of normalization. Three groups of observers—each with a different viewing angle of the walkers (frontal, half-profile, or profile view)—were first trained to name seven unknown walkers over several experimental sessions. During the course of these reinforced training sessions, the walkers were gradually normalized with respect to their size, shape, and gait frequency so that the observers learned to identify the stimuli with less given information. In between the training sessions, four nonreinforced test sessions were conducted, in which all different types of normalizations were used. Additionally, one more test session was conducted at the end of the experiment in which the identification of the walkers was tested over all three viewing angles in order to study generalization from one viewing angle to the others. The authors found that the size of the walkers did not have a significant effect on the identification performance of the observers, whereas the normalization of structure and gait frequency resulted in a deterioration of performance. Moreover, identification in the final test session was best if the observers saw the displays from the same viewing angle as in the training sessions, although considerable transfer to the other viewpoints occurred as well. Even with size, structure, and gait frequency of the walkers normalized, the identification performance at the end of the training sessions was still over 80%, showing that there was much information about individual walkers left in the displays. The present experiments were therefore a continuation of the study of Troje et al. and were designed to investigate in more detail the contribution of specific kinematic components to person identification from biological motion. Only walkers that were normalized with respect to size, structure, and gait frequency were used throughout the present experiments. Thus, the kinematic parameters contained in the Fourier components were the sole source of information used to discriminate among the models. In the test sessions of the first experiment, all but one harmonic remained as individual information in the displays, whereas the other harmonics were normalized. A correct recognition of a walker could therefore only be made on the basis of clues that were provided by this single harmonic. In the second experiment, we adopted the same approach, but this time we examined the relative contributions of the phase- and amplitude-spectra of the gait patterns.

Only a few studies (Bradshaw, Leach, Hibbard, van der Willigen, & Rushton, 1999; Bülthoff, Bülthoff, & Sinha, 1998; Mather & Murdoch, 1994; Troje, 2002a; Troje et al., 2005; Verfaillie, 1993) have examined whether the viewpoint has an effect on the perception of biological motion. According to the *recognition-by-components* theory (RBC; Biederman, 1987), the detection of spatial stimulus properties does not depend on viewing position and allows object recognition even when the image is presented from a novel viewpoint (viewpoint invariance). More recent literature (see Foster & Gilson, 2002, for a review) showed that the viewpoint invariant recognition of objects depends on several parameters, like the complexity of the object or the task of the observer. Bülthoff et al. found that point-light walker displays can be recognized as representing a human structure, independent of the viewpoint. The authors even showed that previous expectations of a familiar object's 3-D structure can override the objective depth information in such displays.

Several studies have dealt with the recognition of static human faces under varying viewpoints (Bruce, Valentine, & Baddeley, 1987; Krouse, 1981; Logie, Baddeley, & Woodhead, 1987; Troje & Bülthoff, 1996). In general, these studies have shown an advantage of the half-profile view. However, many studies on viewpoint dependence did not account for the kinematic aspects of the faces—that is, whether recognition is enhanced by the use of moving faces. Two hypotheses about the role of facial motion can be found in the current literature. Watson, Johnston, Hill, and Troje (2005) found that viewpoint differences between learning and test views only affected faces that were moving in either a rigid or a combined rigid and nonrigid fashion. A general advantage was found for the frontal view, but this was not as pronounced as the effect of the half-profile view in the recognition of static faces. No effects of the viewpoint were found for nonrigid movements alone, supporting viewpoint invariance under this condition. Watson et al. suggested that motion supports the generalization across viewpoints.

Although biological motion can also be classified as nonrigid motion, because of the deformation of the overall structure in the case of locomotion there seems to be an advantage of the frontal view—at least in tasks that aim at person identification or gender classification (Hill, Troje, & Johnston, 2005; Mather & Murdoch, 1994; O'Toole, Edelman, & Bülthoff, 1998; Troje, 2002a; Troje et al., 2005; Watson et al., 2005). There are several methodological differences between these studies and those on face recognition, which makes it hard to compare them. Yet it seems that there are some general differences in how biological motion and faces are affected by varying viewpoints.

In summary, previous findings (Mather & Murdoch, 1994; Troje, 2002; Troje et al., 2005) have suggested that observers are able to recognize individual walking patterns by their kinematics alone and that in general, kinematic cues are more important than structural information in tasks dealing with biological motion. On the other hand, the results of Troje et al. opened the possibility that structural cues are necessary to learn to differentiate the gait patterns and that once a stable knowledge base is established, kinematic cues are sufficient to tell them apart again. This ability would be in accordance with findings from face recognition: Several studies have indicated that motion facilitates the recognition of familiar faces under nonoptimal viewing conditions—for example, blurring, negation, or pixelating (see, e.g., Knight & Johnston, 1997; Lander, Bruce, & Hill, 2001; Lander, Christie, & Bruce, 1999). In contrast, there are contradicting results concerning whether motion enhances the recognition of unfamiliar faces (e.g., Christie & Bruce, 1998; Pike, Kemp, Towell, & Phillips, 1997).

The present study investigated whether observers can learn to identify walkers even when deprived of structural cues right from the beginning of the experiment. The ability to do so would be a further indication that kinematic information is sufficient for the recognition of a walker. Secondly, we focused our attention on the details of kinematic information by examining the relevance of single harmonics in the gait pattern (Experiment 1) as well as on the impact of amplitude- and phase-spectrum manipulations (Experiment 2). Finally, we investigated how observers can generalize across different viewpoints and which components of the kinematic information contribute to viewpoint generalization.

In both experiments, we trained our observers to name seven male walkers whose individual gait patterns had been recorded beforehand. In all trials, we used PLDs of walkers that were normalized with respect to the walkers' size, shape, and gait frequency. In the first experiment, the training portion was followed by a nonreinforced test session in which the stimuli were normalized with respect to different harmonics. Then there was a final test in which we additionally varied the viewpoints from which the walkers were shown. The second experiment followed the same design with the exception that the test stimuli were normalized either for the amplitude or the phase spectrum of the walkers and that no other viewpoint test session was conducted.

EXPERIMENT 1
The Role of Fourier Components

The main question of the first experiment was whether all the relevant information about a walker is contained in the first harmonic, which explains the largest part of the overall variance in a walking pattern, or whether higher order harmonics are sufficient or necessary for person identification. To examine this, we trained our observers to name seven walkers and then tested them on normalized versions such that only the first, second, or higher order harmonics still contained individual information. If the amount of variance explained by the harmonics is crucial for identification, the performance should be high when the first harmonic is included in the model, but not above chance level when only second or higher order harmonics are used. An alternative hypothesis was that the first harmonic represents primarily a general human walking pattern and that individual information is contained in higher order harmonics. In this case, we should find a better identification performance in conditions when only the second or even only higher order harmonics are used in the displays of the walkers. Furthermore, we examined the importance of the harmonics under varying viewpoints—that is, whether there is an interaction between the harmonics and the viewing angle of the displays.

Method

Subjects. Eighteen subjects (9 female, 9 male, 21–40 years of age, $M=25.89$ years) participated in the experiment. All of them were students at Ruhr-Universität-Bochum who received course credit for their participation. Their visual acuity was normal or corrected-to-normal.

Materials. A motion capture system equipped with 9 CCD cameras (Vicon 512; Oxford Metrics, Oxford, U.K.) was used to record the walking data of 40 men, all of whom were students or staff at Ruhr-Universität-Bochum. Based on a set of 41 retroreflective markers, the locations of 15 anatomical points inside the body were computed by employing commercially available software (Bodybuilder; Oxford Metrics) for biomechanical modeling. Most of them corresponded to major joints (shoulders, elbows, wrists, hips, knees, ankles). The details of this process were described in a previous study (Troje, 2002a). The time series containing the Cartesian positions of these 15 calculated markers was then decomposed into a Fourier expansion. The time-invariant part of this decomposition contains structural, anthropometric data p_0, whereas the time-dependent terms p_j and q_j contain information about the kinematics of the single markers (Troje, 2002b):

$$p(t) = p_0 + \sum_{j=1}^{n} \left[p_j \sin(j\omega t) + q_j \cos(j\omega t) \right]. \tag{1}$$

The resulting representation of the individual walkers is morphable—that is, convex linear combinations of existing walkers result in normal walking patterns. In particular, the average across a number of walkers results in a walking pattern that appears to be as real as any of the constituting walkers (Troje, 2002b; see also the demonstration at biomotionlab.ca/Demos/BMLwalker.html).

For the present experiments, we used 20 walkers whom we chose from a database of the 40 male walkers by excluding the 10 most distinctive and the 10 least distinctive walkers. Distinctiveness was defined in terms of the Euclidean distance of each walker from the overall average. For each particular experimental subject, 7 walkers were randomly selected from this set of 20 walkers. In this way, it was possible to use the natural variance in our database without making the task too easy or too difficult.

All walkers were first normalized to unit size. The data were then subjected to a discrete Fourier analysis (Equation 1). Figure 1 shows the amplitudes of the different harmonics averaged across all 20 walkers. Because the amplitude declines rapidly, the Fourier expansion was clipped after the 5th harmonic ($n = 5$ in Equation 1). The time-invariant component p_0 of the Fourier expansion was then replaced by the average of this component computed across the seven walkers who were used for a particular observer. This resulted in all point-light walkers having the same overall body structure. Finally, we also normalized all walkers to the same average gait frequency ω. The normalization of this parameter was done to restrict the individual information about the walkers to the motions as defined by the Fourier components. These normalized walkers (called base condition in the following) were used in all training sessions.

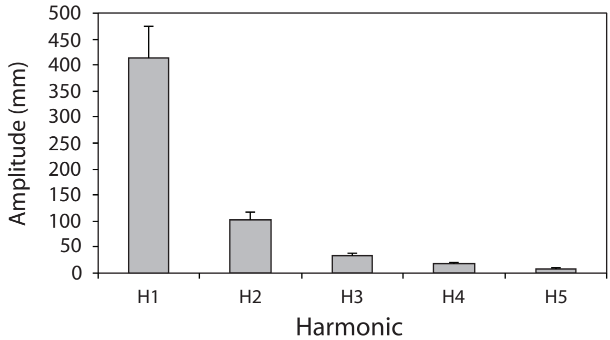

Figure 1. Mean amplitude of each harmonic over all 20 walkers. Error bars indicate standard deviations.

Modified versions for the test sessions were constructed in the following way: We first computed the average across the seven walkers used for a particular observer. For the first test set, we replaced the first harmonic (p_1, q_1 in Equation 1) of this average walker with the respective first harmonic of each individual walker. Thus, we created seven different walkers who differed only with respect to the first harmonic (called the H1 condition). Therefore, any possible differentiation between the walkers could only be caused by the perceptual significance of the individual first harmonic of each walker.

Comparable procedures were applied to create test sets of walkers who differed only with respect to the second harmonic (H2 condition) or to the third to fifth harmonics (H3 condition). We grouped the third to fifth harmonics together because their power was very small, and visual analyses of the walkers suggested that there was virtually no difference between them if we used only one of these harmonics alone.

The displays were shown on a 19-in. screen (Iiyama Vision Master Pro 450), and the subjects were placed in front of the screen at a distance of 70 cm. The visual angle of the displays subtended about 4.8º in height and 2º in width under maximum excursion. Stimuli were rendered online at a rate of 85 Hz, which was synchronized with the graphics board's screen refresh rate.

Design and Procedure. During training and the first test session, each observer saw the point-light walkers always from the same viewpoint. Equal numbers of observers were shown displays in frontal view (FV, 0º), half-profile view (HV, 30º), or profile view (PV, 90º). In the latter two groups, half the subjects saw the walkers facing to the right side, and half saw them facing to the left side. We used no occlusion in the displays, so every marker was visible from all the viewpoints at all times. Subjects were randomly placed into one of three training groups according to these viewpoints, and their gender was balanced within the groups. The experiment was conducted on two consecutive days for each subject. On the first day, there were four training sessions in which the observers learned to name the seven walkers that were selected randomly for each of them. Only stimuli from the base condition were used in the training sessions so that the observers learned to name point-light walkers who were normalized with respect to their size, shape, and gait frequency from the outset. In each trial, one of the walkers was shown to the observer for 3 sec. After the display, seven red buttons with fictitious male names of the walkers appeared in alphabetical order at the top of the screen, and the subject had to click on one of the names. If the answer was incorrect, the button with the correct name flashed green for 1 sec before proceeding to the next trial. In each session there were 140 trials grouped into 10 blocks. Every walker was shown twice in each block, with the order of the walkers randomized within blocks. The displays of the walkers were randomly phase shifted to rule out the possibility that the walkers could be identified by characteristic dot configurations at the beginning or end of a trial. If the answer was correct, nothing happened before continuing to the next trial. There was an interstimulus interval of 1 sec between the response of the observer on one trial and the start of the display in the next trial. After each complete training session, there was a break of at least 2 min in which the subject was allowed to leave the room.

Test Session A immediately followed the four training sessions of the first day. In this session, the base walkers as well as the H1, H2, and H3 walkers were shown to the subjects from the same viewing angle as in the training sessions of the respective subject. The procedure was the same as in the training sessions, except that no feedback was given to the observers. Test Session A consisted of 140 trials (7 walkers × 4 types × 5 phase-randomized repetitions). The order of the trials was randomized across the whole session.

On the second day, we first conducted two more training sessions to refresh the subjects' knowledge of the walkers. After that, Test Session B was conducted. The procedure and the stimuli were the same as those in Test Session A, but this time all three possible viewpoints were used. A total of 168 trials were conducted (7 walkers × 4 types × 3 viewpoints × 2 repetitions). The order of the trials was randomized across the whole session. The subjects were not told that they were going to see modified versions of the walkers in either of the test sessions.

Results and Discussion

Analysis of the point-light walkers. Preceding the analyses of the results, we computed the average power of the first five harmonics across the 20 walkers. The power reflects the contribution of the individual components to the overall variance. The relative power was 91.2%, 6.4%, 1.4%, 0.7%, and 0.3%, respectively. The square root of the power is equal to the amplitude of the Fourier components, scaled in terms of marker displacement averaged across the 20 walkers, time, and the 15 markers. These amplitudes are plotted in Figure 1. As can be seen, the average amplitude of the first harmonic is 414 mm, with a standard deviation of about 60 mm. Both values are about four times as high as the respective values for the second harmonic and much higher than for the other harmonics. This indicates that a large part of the overall motion is expressed by the first harmonic and that the differences between the walkers are also greatest for this harmonic.

No significant differences were found between male and female participants for any of the dependent variables either during training or in the test sessions, so the results presented here are pooled over both groups.

Training sessions. Starting from about chance level (14.3%), all three groups quickly improved their performances in identifying the walkers (Figure 2). In the last training session of the 1st day (i.e., in Training Blocks 31–40), the FV, HV, and PV groups reached a correct average response level of 76%, 71%, and 71%, respectively (mean level: 73%). In the final training session (i.e., in Training Blocks 51–60, at the end of the 2nd day), the performances reached an average level of 86%, 78%, and 87%, respectively. The overall performances of the groups averaged over all six training sessions were at 68%, 63%, and 65%, respectively. A univariate ANOVA showed that the differences between the overall performances did not reach statistical significance ($p > .05$ in all cases).

Observers were quickly able to discriminate seven different walkers with whom they were previously unfamiliar, even though information about structure, size, and gait frequency was removed from the data set. The walkers who were shown to each subject were selected on a random basis, so this finding could not have been caused by some walkers who were easily identified. Additionally, by choosing for the walkers to have medium distinctiveness, we ruled out the possibility that some subjects had to discriminate walkers who were very different from each other. The identification rate at the end of the training sessions was at about 80%, which is comparable to the findings of Troje et al. (2005). This means that in the latter study, high identification levels of normalized walkers

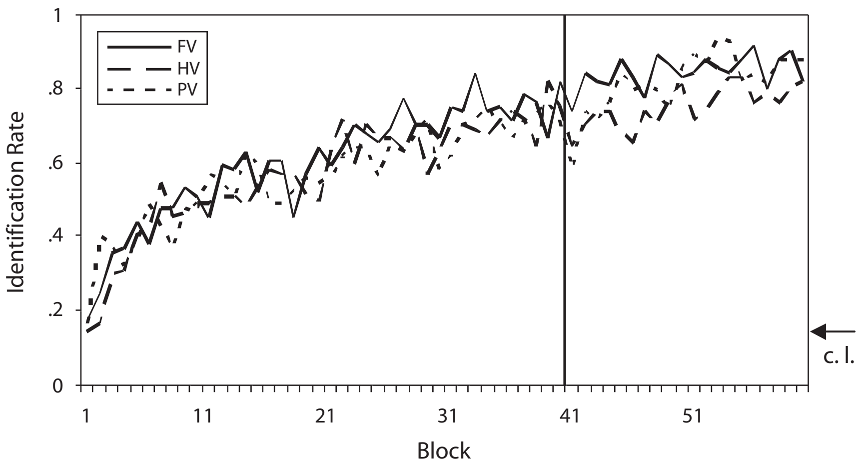

Figure 2. Learning curves of the three experimental groups in Experiment 1. Every walker was shown twice in each block. The solid line represents the end of the first experimental day; the arrow indicates chance level. FV, frontal view; HV, half-profile view; PV, profile view.

were not caused by the fact that the walkers were shown in the original way beforehand, thereby transferring learning effects to subsequent sessions.

Test Session A. A univariate repeated measures ANOVA with type of information (info, levels base, H1, H2, and H3) as a within-subjects factor and training viewpoint (view, levels FV, HV, and PV) as a between-subjects factor was conducted, with the number of correct identifications of the walker stimuli as the dependent variable.

The factor info had a significant effect on walker identification [$F(3,45) = 64.73$, $p < .001$]. The performance deteriorated with the order of harmonics that was used in the displays (Figure 3A). Bonferroni-corrected post hoc tests revealed significant differences between every single condition (all ps $< .02$). In the base condition, the displays were the same as those shown to the observers in the training sessions. The level of correct identifications in this condition (70%) did not differ from the average level of the previous training session [73%; $t(17) = 1.272$, n.s.]. In the H1 and H2 conditions, the levels of identification (50% and 29%, respectively) were still above chance level (paired t tests, all ps $< .03$). The value for the H3 condition (20%) did not reach a significant level after Bonferroni correction. There was no significant main effect for either the factor view [$F(2,15) = 1.07$, n.s.] (Figure 3B) or the interaction of factors info and view [$F(2,15) = 1.41$, n.s.]. Figure 3C shows that the pattern of identification remained the same in all of the three groups. Although there was no overall interaction between the factors, a closer examination of Figure 3C suggests that there could have been significant differences between the groups at single info levels, especially at the H1 condition for the HV group. To control for these effects, we additionally conducted post hoc tests between all groups for every single condition, but none of these comparisons reached statistical significance (all ps $> .05$).

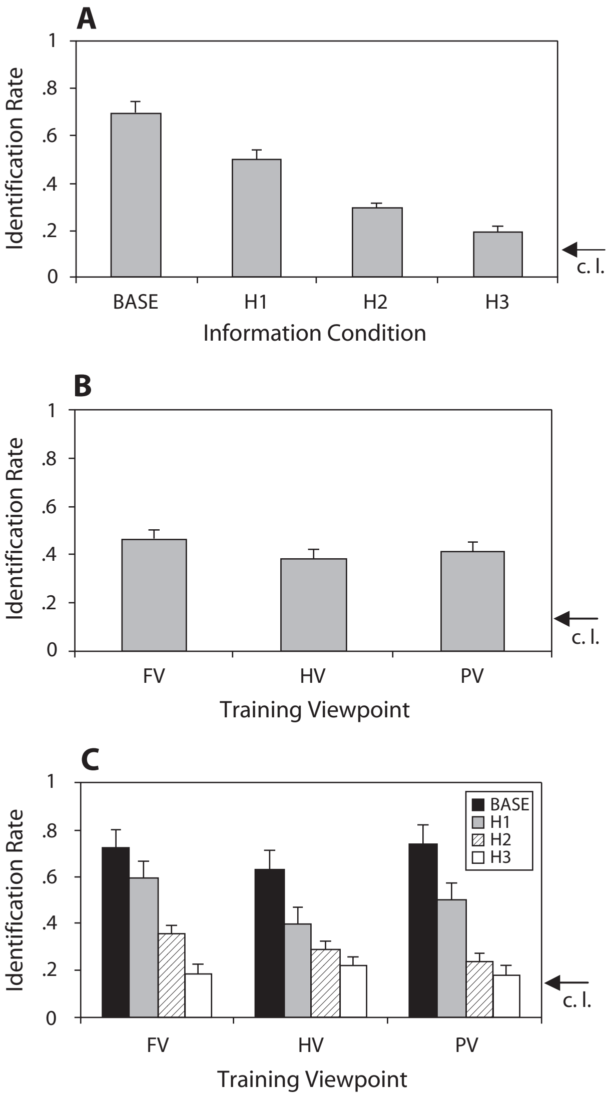

Figure 3. Identification performances in Test Session A: Results for the type of information (A), training viewpoints (B), and interaction between the factors (C). Error bars indicate standard error of the mean; arrows indicate chance level. BASE, base condition; FV, frontal view; HV, half-profile view; PV, profile view.

The lack of differences between the groups in the training sessions as well as in Test Session A in the current study corroborates the results of Troje et al. (2005). We found that the normalization of body structure affected identification performance especially from a frontal view, leading to a cancellation of the frontal-view advantage found for the unmodified veridical walkers in this group. This finding indicated that structural information mainly contributed to the performance of the FV group, whereas it was used to a much lesser degree from the other two viewpoints. No structural cues that could have been used by the FV group, however, remained in the displays of the walkers in the current study. On the other hand, it appears that structural information is not necessary for the identification of a person, because all groups performed well above chance level in the training sessions as well as in the base, H1, and H2 conditions of Test Session A. However, the performances obtained in the present study never reached the same levels as those in the previous study (Troje et al., 2005) in which identification in the FV group approached 100% if structural cues were available. At the end of the present experiment, performance showed virtually no increase beyond 80%–90%.

Although the levels in the base condition of Test Session A were comparable to the respective levels in the fourth training session, performance deteriorated as soon as the subjects encountered walker displays deprived of parts of the kinematic information. However, performance in all groups was still above chance level in the H1 and H2 conditions. These results clearly indicate that the first and second harmonics provide sufficient information to adequately represent a walker in an identification task. Regarding our hypotheses, one can say that neither the absolute amount of variance explained by a harmonic nor its variability across walkers is necessarily predictive of the information used for person identification. The first harmonic explains on average about 91% of the variance in an individual's walking pattern from the data set used in this study, and it is the most important single factor of kinematic information that was varied in our study, with

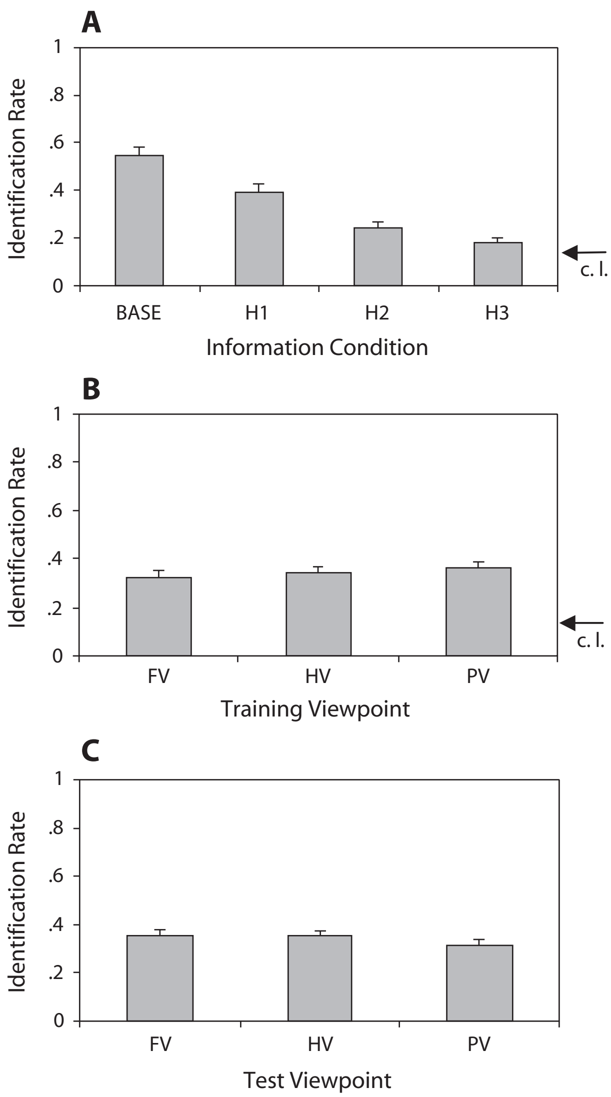

Figure 4. Identification performances in Test Session B: Results for the type of information (A), training viewpoints (B), and test viewpoints (C). Error bars indicate standard error of the mean; arrows indicate chance level. See Figure 3 for an explanation of abbreviations.

an average of 50% correct identifications (i.e., more than three times higher than chance level) under the H1 condition. However, the performance in this condition was significantly lower than that in the base condition, showing that some important information was already missing. The second harmonic explains little more than 6% of the variance, but observers were still able to correctly discriminate among the walkers on about 30% of all trials. The results strongly support the hypothesis that the second harmonic also contains significant information for person identification. We can also reject the hypothesis that the first harmonic describes a general human walking pattern, because otherwise observers would not have been able to discriminate among the walkers by seeing only the first harmonic as individual information. The first harmonic comprises mainly the horizontal movements of the legs and the arms as well as the lateral sway of the upper body, whereas the second harmonic contains a relatively big portion of the vertical movement in a gait pattern. The amplitudes of horizontal and lateral movements are much larger than the amplitudes of vertical motion. If the amount of motion determined the significance of a component for person identification, then there should have been an advantage when the walkers had been shown from a profile view, which is the best viewpoint to perceive the most concise motions. Furthermore, we should have seen an interaction between the viewpoint and the information condition, with the performance under the frontal view being worse than that from the other two viewpoints for the H1 condition, which was not the case.

Test Session B. In this test session, we had one additional within-subjects factor, namely the test viewpoint of the stimuli (test, levels FV, HV, and PV). The remaining factors were the same as those in Test Session A: view (between subjects, 3 levels) and info (within subjects, 4 levels). We conducted a repeated measures ANOVA with these three factors on the correct identification rate.

In accordance with Test Session A, we found a highly significant main effect for factor info [$F(3,45) = 50.80$, $p < .001$], showing decreasing performance with higher order harmonics (see Figure 4A). Multiple *t* tests revealed that all conditions were significantly above chance level (all *p*s $<$ .03). Again, when we corrected the *p* values for the number of tests conducted, the value of the H3 condition did not reach a significant level anymore. Pairwise comparisons ($p < .01$) between the conditions revealed significant differences for all but the comparison between the H2 and the H3 conditions. No effect was found for factor view [$F(2,15) = 0.21$, n.s.] (Figure 4B), but there was a significant main effect of factor test [$F(2,30) = 4.04$, $p = .028$] (Figure 4C). Testing with the profile view produced a slightly worse performance than testing with the half-profile view.

In the light of previous results (e.g., those of Mather & Murdoch, 1994, and Troje et al., 2005), the advantage for the half-profile test view is rather surprising. The half-profile view is between the other two viewing angles, so one might suppose that there is a general advantage for this viewpoint. This is because the displays still contain some of the information that was perceived from a more

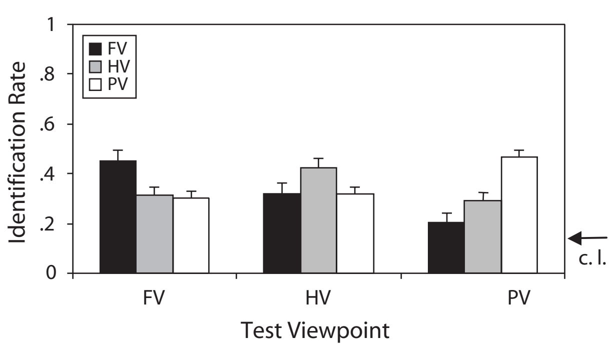

Figure 5. Interaction of factors view (shading) and test (*x*-axis) in Test Session B. Error bars indicate standard error of the mean; the arrow indicates chance level. See Figure 3 for an explanation of abbreviations.

extreme view and are thus more similar to the familiar view that was used in the training sessions. On the other hand, there was no advantage for the half-profile view over the frontal viewpoint. Maybe the effect is due to an asymmetry between the frontal and the profile view that seems to appear in Figure 5: Generalization from the profile view to the frontal view seems to be easier than generalization from the frontal view to the profile view.

Figure 5 also indicates a significant two-way interaction between the training and the test view, which was confirmed by our analyses [$F(4,30) = 17.36$, $p < .001$]. Performance in Test Session B was always best if the observers saw the displays from the same viewing angle as that in the training sessions. No interaction effects were found for the other two combinations of the factors in Test Session B (info × view and info × test).

The interaction between the factors view and test corroborates the results of Troje et al. (2005), who found the same results. This effect is clearly caused by a benefit for test views that were familiar to the training groups, whereas the performance under the two views that were unfamiliar to the respective groups did not differ from each other. This shows that the identification performance does not deteriorate linearly with an increasing amount of rotation between the training and the test view. On the contrary, there is already an obvious forfeit after a rotation of 30º from the frontal to the half-profile view (45% vs. 31% recognition). It remains to be seen whether a rotation of less than 30º affects performance or whether there is a discrete border of rotation that leads to a drop of performance when crossed.

We also found a significant three-way interaction between the factors in Test Session B [$F(12,90) = 3.60$, $p < .001$]. Figure 6 shows that there is a similar pattern of identification performance over all info conditions, but the gradient between the test conditions becomes shallower with the higher order harmonics.

In the first experiment, we split up the walking patterns to examine the contribution of the discrete harmonics to the identification of the walkers. We saw that the first harmonic is most important for this task, but that the second harmonic contributes much more than would be expected to the overall variance of the walking pattern itself as well as to the variability among walkers. Another way to represent the kinematic information of a walking pattern is to describe it as the amplitude and the phase values of the single markers. This was done in the second experiment.

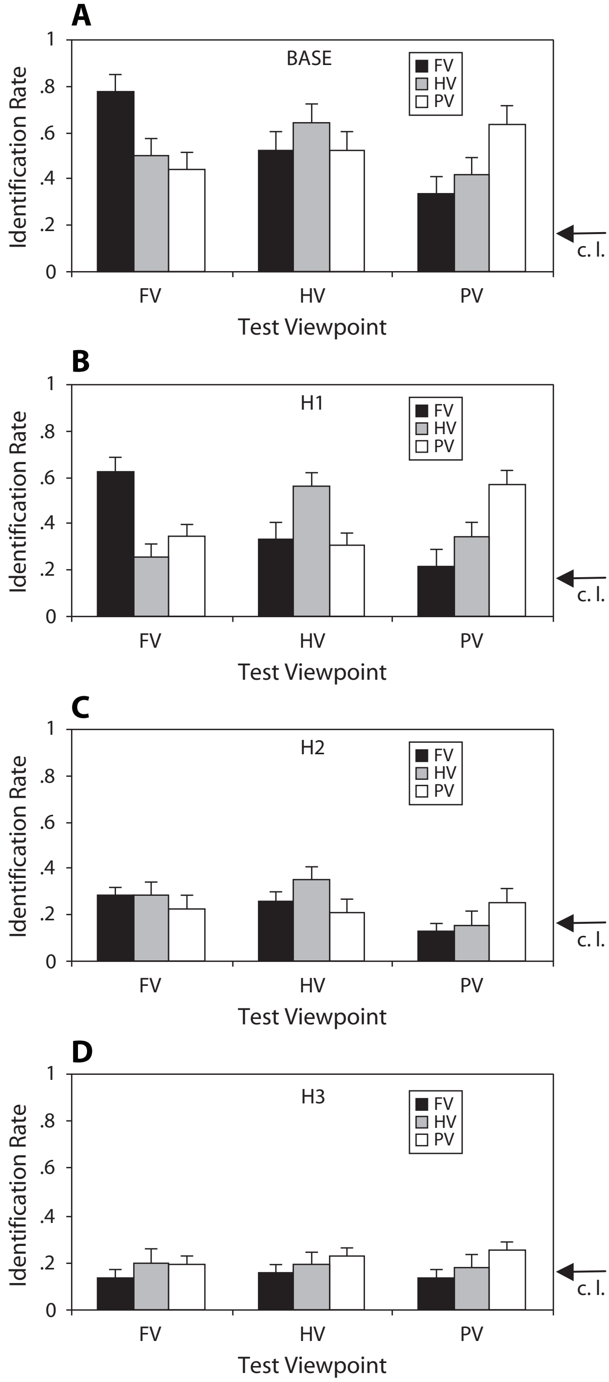

Figure 6. Interaction of factors view (shading) and test (*x*-axis) under the four different info conditions. Error bars indicate standard error of the mean; arrows indicate chance level. See Figure 3 for an explanation of abbreviations.

EXPERIMENT 2
The Role of Phase and Amplitude

In the previous experiment, we used Fourier analysis to decompose biological motion into its frequency components. We investigated the role of single components by creating stimuli in which all other information was equalized across walkers. In the second experiment, we adopted the same approach to look at the differential role of amplitude and phase information. Whereas the amplitude spectrum determines the extent of displacement of the 15 markers, the phase spectrum contains information about the temporal relation between the movements of the markers and their spatial components.

Method

Subjects. Eighteen subjects (13 female, 5 male, 19–42 years of age, $M = 26.11$ years) participated in the experiment. Because previous findings did not suggest any sex differences in the performances of the observers, we did not balance the number of male and female subjects in this study. All participants were students at Ruhr-Universität and were either awarded credits for completion of their psychology courses or received 20 euros for their participation.

Materials. The sample of 20 walkers—normalized by size, shape, and gait frequency—as well as the equipment were the same as those used in Experiment 1, and seven walkers were randomly selected as target stimuli for each subject in the training sessions. For the subsequent test session, we generated walkers who differed either only in the amplitude of the Fourier components or in their phase. For each harmonic j, vectors for amplitude a and phase ρ were derived from vectors p and q in Equation 1 as follows:

$$a = \sqrt{\left(p^2 + q^2\right)}, \qquad \rho = \arctan\left(\frac{q}{p}\right). \tag{2}$$

The vectors encoding amplitude or phase for all harmonics of a single walker were replaced by the average values computed across the seven walkers used for the respective subject. Two sets of modified walkers were created. In the amplitude condition, walkers retained their individual amplitudes, but the vectors encoding phase were replaced with the averaged version. In the phase condition, the walkers retained their individual phase spectra, but the vectors encoding amplitude were replaced with the averaged versions.

Although we had used a custom-designed C program for Experiment 1, the second experiment was conducted with MATLAB and the Psychophysics Toolbox extension (Brainard, 1997). Moreover, the size of the stimuli was somewhat different from the sizes used in Experiment 1. Walkers in this experiment subtended a viewing angle of 8.1º in height and 3.3º in width under maximum excursion.

Design and Procedure. The design of the second experiment was the same as that of the first experiment, with only few exceptions. The observers did not complete a test session at the end of the first day. In the first experiment, Test Session A served to collect more data about the role of the harmonics, independent of the test viewpoint. Because we found comparable results in both test sessions of the first experiment, we decided to omit the first test session in the second experiment. The feedback procedure was slightly adjusted: When the subject clicked on the correct name for a walker, the button flashed green for one second; when the subject clicked on the wrong name, the button with the correct name flashed red. At the end of the second day, observers completed a single test session. Stimuli were either the original walkers (base)—the same as those used in the training sessions—or walkers from the amplitude or phase stimulus sets. All three viewpoints (FV, HV, and PV) were used as possible viewing angles of the displays. The test session consisted of 189 trials (7 walkers × 3 conditions × 3 viewpoints × 3 repetitions).

Results and Discussion

Training sessions. As they did in Experiment 1, identification rates started from about chance level, but quickly improved over time (Figure 7). In the last training session, the FV, HV, and PV groups reached identification rates of 89%, 92%, and 75%. The overall values over all training sessions were 73%, 77%, and 59%. A comparison of the learning curves of the first and the second experiment suggests that although there were no obvious differences between the groups in the first experiment, the FV and the HV groups showed higher performance levels than the PV group in the second experiment. However, t tests failed to reveal significant differences either for the overall performances of the groups or for the performance in the last training session (all $ps > .05$). Looking at the data of single subjects showed that the lower mean values in the PV group are due to one single participant who performed exceptionally poorly.

Test session. We conducted a repeated measures ANOVA on the rate of correct identifications with the factor training viewpoint (view, levels FV, HV, and PV) as a between-subjects variable, and the factors test viewpoint (test, levels FV, HV, and PV) and information (info, levels base, amplitude, and phase) as within-subjects variables. No effects were found for the factors view [$F(2,15) = 1.49$, n.s.] or test [$F(2,30) = 0.91$, n.s.] (Figures 8A and 8B). A highly significant main effect was found for the factor info [$F(2,30) = 96.45$, $p < .001$] (Figure 8C). Post hoc tests revealed that every single comparison of the info conditions showed a significant difference, with the original stimuli leading to the best results (58.4%), followed by the stimuli that contained only information about amplitude (46.7%). Stimuli with phase-only infor-

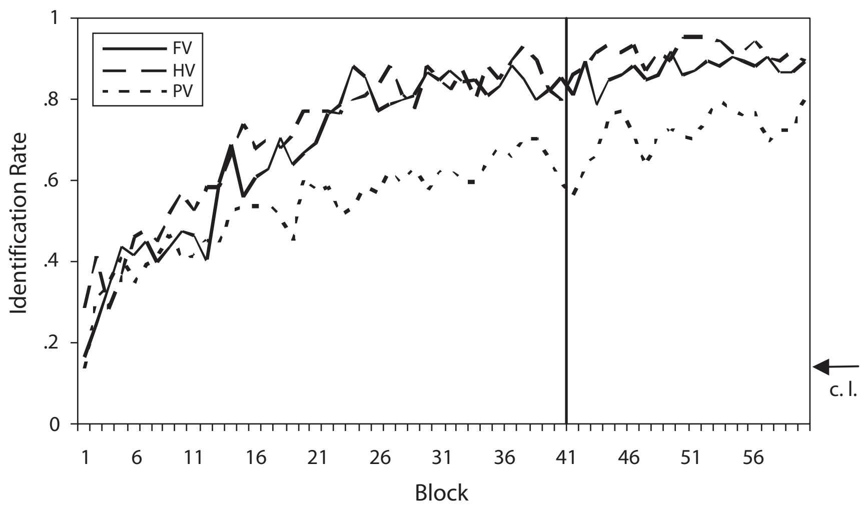

Figure 7. Learning curves of the three experimental groups in Experiment 2. Every walker was shown twice in each block. The solid line represents the end of the first experimental day; the arrow indicates chance level. See Figure 3 for an explanation of abbreviations.

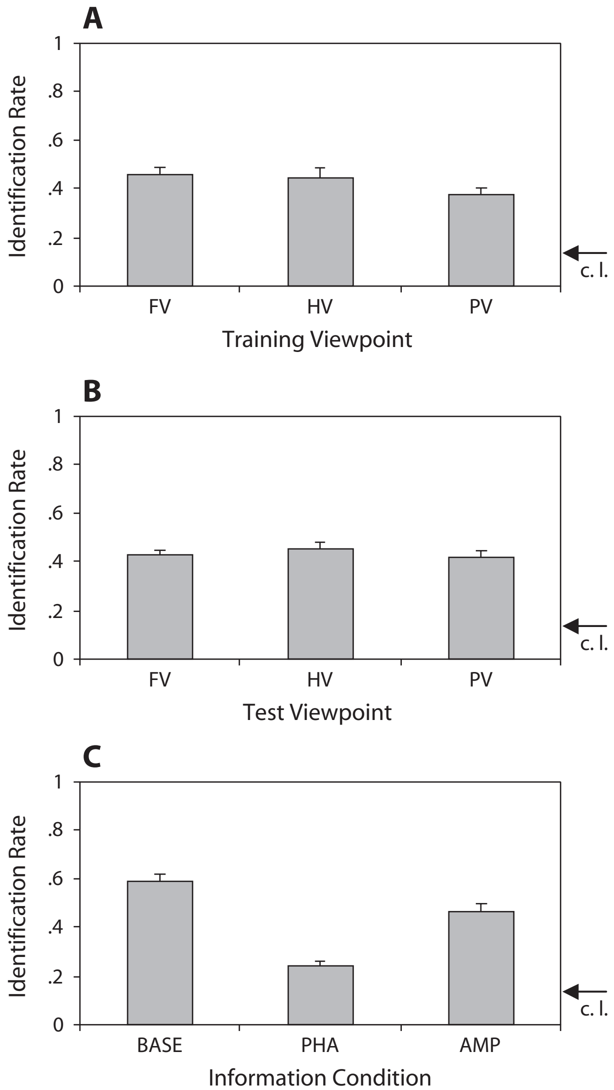

Figure 8. Main effects for the test session of Experiment 2: Results for factors view (A), test (B), and info (C). Error bars indicate standard error of the mean; the arrows indicate chance level. FV, frontal view; HV, half-profile view; PV, profile view; BASE, base condition; PHA, phase condition; AMP, amplitude condition.

mation resulted in the worst identification (23.3%). All three values, however, differed significantly from chance level ($ps < .001$).

The missing main effect for the test view is in contrast to the results of Experiment 1, where we found that the half-profile test view resulted in a slightly better performance than that of the profile view. The effect was weak in the previous experiment, and the absence of a similar effect in Experiment 2 may simply be due to lack of statistical power of the data.

With respect to the information condition, the results show that the contribution of the individual amplitudes of the markers of a point-light walker is far more important than the temporal relations of the dots to each other, represented by their phases. On the other hand, however, phase information alone is enough to correctly identify the walkers in 23% of the cases, which is much higher than chance level. Theoretically, this level could already be reached if one of the seven walkers randomly selected for each subject had a very characteristic walk and could therefore be identified with a high accuracy. We therefore cross-checked the walkers who were selected as the target stimuli with each subject, along with the respective identification rate under each condition. We did not, however, find evidence that there were specific walkers who could be identified easily by all the observers for whom they had been used. We conclude that the phase spectrum of a walker has an effect on his identifiability, even though it is far less important than the amplitude.

As in Experiment 1, we found a highly significant interaction effect between the factors view and test [$F(4,30) = 17.84$, $p < .001$], which is shown in Figure 9A. Again, performance was best if the walkers were shown from the same viewpoint as in the training sessions, and performance decreased with the amount of rotation away from the training viewpoint.

Another significant interaction was found between the factors test and info [$F(4,60) = 3.00$, $p = .025$]. We conducted additional repeated measures ANOVAs on the differences between the information conditions, separately for each test viewpoint. From a frontal view, all three information conditions differed significantly from each other ($ps < .005$). The best performance was found in the base condition (58.8%), followed by the amplitude condition (40.8%) and the phase condition (25.7%). For the half-profile view, we found no difference between the base and the amplitude conditions (60.1% vs. 50.9%), but performances under both conditions were significantly better than those in the phase condition (23.8%; $ps < .001$). We found the same significance pattern for the profile view, with 56.3% identification rate under the base condition, 48.5% for the amplitude condition, and 20.6% for the phase condition (Figure 9B).

The phase spectrum of a gait pattern only seems to be utilized from a frontal view. The reason for this may have to do with the fact that the largest amplitudes occur perpendicular to the frontoparallel plane. Hence, in the frontal view, information derived from the amplitude becomes less reliable, and the phase spectrum of the gait pattern obtains greater importance in comparison with the other viewpoints. We suppose that the interaction between the factors is caused by a reduced reliability of information about the amplitude spectrum from a frontal viewpoint.

Furthermore, we found a significant three-way interaction between the factors view, test, and info [$F(8,60) = 6.74$, $p < .001$]. The results for the base and amplitude conditions resemble the findings that have already been shown in Figure 9A. This interaction is leveled out when the amplitude of the walking patterns is averaged, because of the low overall performance under this condition (Figure 10).

SUMMARY AND GENERAL DISCUSSION

In this study, we focused our attention on how person identification from biological motion is influenced by kinematic parameters, namely the harmonics as well

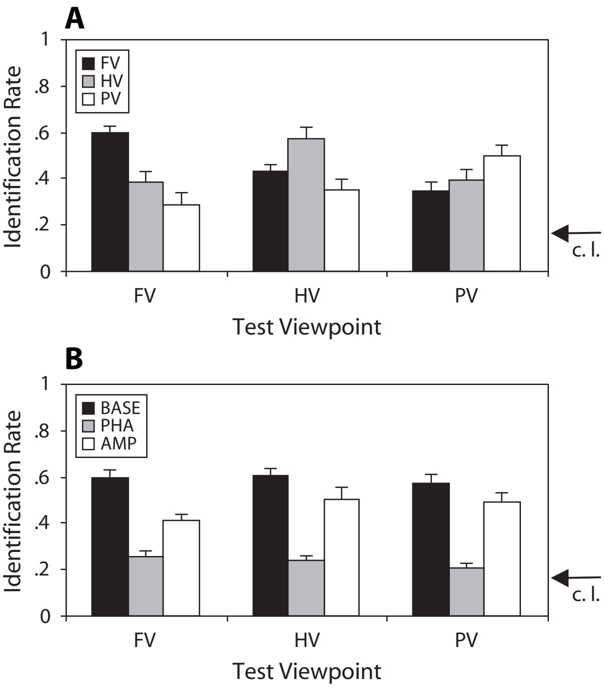

Figure 9. Interactions in the test session of Experiment 2: Between factors view (shading) and test (*x*-axis) (A), and between factors info (shading) and test (*x*-axis) (B). Error bars indicate standard error of the mean; the arrow indicates chance level. See Figure 3 for an explanation of abbreviations.

as the amplitude and the phase spectra that result when a walking pattern is decomposed using Fourier analysis. This was done for three different viewpoints: frontal, half-profile, and profile. Observers were able to learn to discriminate seven male walkers independently of the viewing angle under which the training was conducted. We found that the first and second harmonics both provided sufficient information to identify individual walkers. The task could also be solved at an accuracy above chance level when only the amplitude or only the phase information remained in the displays, although the former led to significantly higher performance levels. Removing information about the phase spectrum impaired recognition much more when the walkers were shown from a frontal viewpoint than when they were shown from the other two viewing angles. There was no structural information left in the displays that could be used for the task, meaning that kinematic parameters are sufficient to name the walkers. Other studies (Mather & Murdoch, 1994; Troje, 2002; Troje et al., 2005) found an overall advantage for the frontal view, which could not be replicated here. This was probably caused by the lack of structural information in the current displays. Up to now, the only study that used structural vs. kinematic information in an identification task was conducted by Troje et al. These authors gradually normalized the PLDs with respect to size, shape, and gait frequency, whereas we used displays that were normalized with respect to all three parameters from the outset of the experiment. Given the fact that the observers were still able to solve the task at a high accuracy level, we conclude that structural information is not of central importance for person identification from biological motion. However, we did not explicitly test how performance is affected when the complete kinematic information is normalized and only the structure of the walkers remains unchanged. From the results of the present study as well as those of Troje et al., one might assume that identification from structural cues alone would result in much lower accuracy levels. On the other hand, subjects might adopt a different strategy to discriminate gait patterns if only structural cues are available, so that differences in body structure are more readily perceived.

The first and second harmonics were both employed for the identification task: An elimination of one of these harmonics from the displays resulted in a significant drop of the recognition rates in relation to the original stimuli. In contrast, a combination of the third to fifth harmonics was not enough to obtain performance above chance level. Although the second harmonic explains on average only about 6% of the overall variance of a gait pattern from our data set, it is nevertheless important for the recognition of individual walkers. We thus find a clear difference between the physical walker space that is dominated by the first harmonic and the perceptual space in which both harmonics contribute significantly. If one examines the visualizations of the single harmonics of a gait pattern, one can see that the second harmonic contains a predominant amount of the vertical motion. In comparison with the horizontal movements, this is not very pronounced, but obviously it is sufficient to discriminate among individuals' locomotion patterns. This fact is possibly based on the dynamics of a walk—that is, on the energy that is needed to overcome the gravitational forces. Several studies have shown that observers are sensitive to the underlying dynamics of biological motion (e.g., Jokisch & Troje, 2003; Runeson & Frykholm, 1981, 1983). If observers are also sensitive to the individual dynamic pattern of a walker, the second harmonic may contain a reasonable amount of information to identify these patterns. On the other hand, higher order harmonics do not seem to provide much additional information. Even though we have not tested this explicitly, we assume that a second-order Fourier representation is perfectly sufficient to represent an individual's walking pattern. Higher order contributions may simply encode measurement noise.

The amplitude spectrum of a gait pattern is more important than the phase spectrum, with the latter only being relevant primarily when the stimuli are shown from a frontal perspective. To a very limited degree, the relative phases of the markers are also used to identify point-light walkers from a half-profile view and a profile view. It might be instructive to examine whether there are specified sets of markers that lead to this identification from the phase spectrum—for example, the forward swing of one arm in relation to the movement of the legs, or a more subtle one, like the vertical movement of the hips in relation to the lift of the legs.

Related to the question about the role of relative phase information is the question of whether it is necessary to see the whole body for a successful accomplishment of an

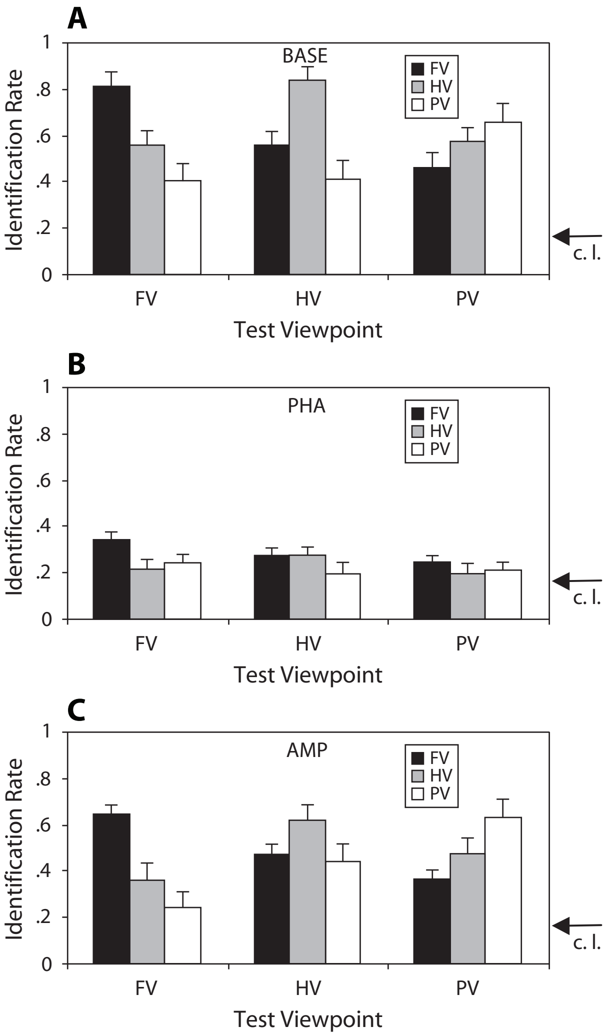

Figure 10. Interaction between factors view (shading) and test (*x*-axis), shown separately for each info condition. Error bars indicate standard error of the mean; the arrow indicates chance level. See Figure 3 for an explanation of abbreviations.

identification task or whether certain body parts might be sufficient. Kozlowski and Cutting (1977) suggested that even the ankle movements of a walker are sufficient to recognize the sex of the person, although this assumption was corrected later (Kozlowski & Cutting, 1978). Hill, Pollick, and colleagues (Hill & Pollick, 2000; Pollick, Lestou, Ryu, & Sung-Bae, 2002; Pollick, Paterson, Bruderlin, & Sanford, 2001) showed that observers are able to estimate the affect of a person from arm movements, but that they are inefficient in estimating the gender of the person from these kinds of motions. To our knowledge, the role of specific body parts has not yet been examined in a person-identification task.

A rotation of the displays between training and test sessions leads to a decline of performance. It is not clear which amount of rotation causes this deterioration, because we did not find differences between views that were unfamiliar to the observers. This includes in particular the half-profile view, which is somewhere in between the other two views. One might assume that it is easier to generalize from or to this viewing angle with respect to the other two, but this is clearly not the case. In the test sessions of the two experiments, we used only very coarse rotations of 30º or 90º with respect to the frontal viewpoint. A finer gradation would be necessary to measure thresholds of stimulus rotation that impair the performance.

Although performance declined with an increasing viewing angle, recognition was always significantly above chance level as long as the walker versions from the training sessions were used in the test sessions. This indicates that the observers did not only recognize a pattern of simple point-light trajectories, but that there was a more general representation of a human structure that could be built from all three viewpoints and also be recalled from any of the other two viewing angles. In case of a representation of the animations as simple trajectories, this recognition from other viewpoints should not have been possible. The ability to recognize the walkers from different viewpoints must be based on a three-dimensional structure that connects the point lights and builds a foundation of how the complete animation pattern changes when seen from a different viewpoint. Otherwise, it would be hard to imagine how the two-dimensional projections of single trajectories can be recognized, especially after a rotation of up to 90º, which includes a totally different offset and motion pattern for individual point lights, such as the wrists or ankles.

AUTHOR NOTE

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