

Body Configuration Modulates the Usage of Local Cues to Direction in Biological-Motion Perception

Masahiro Hirai^{1,2}, Dorita H. F. Chang³, Daniel R. Saunders^{1,4}, and Nikolaus F. Troje^{1,5}

¹Department of Psychology, Queen's University; ²Japan Society for the Promotion of Science, Tokyo, Japan;

³School of Psychology, University of Birmingham; ⁴Schepens Eye Research Institute, Harvard Medical School;

and ⁵School of Computing, Queen's University

Psychological Science

22(12) 1543–1549

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DOI: 10.1177/0956797611417257

http://pss.sagepub.com



Abstract

The presence of information in a visual display does not guarantee its use by the visual system. Studies of inversion effects in both face recognition and biological-motion perception have shown that the same information may be used by observers when it is presented in an upright display but not used when the display is inverted. In our study, we tested the inversion effect in scrambled biological-motion displays to investigate mechanisms that validate information contained in the local motion of a point-light walker. Using novel biological-motion stimuli that contained no configural cues to the direction in which a walker was facing, we found that manipulating the relative vertical location of the walker's feet significantly affected observers' performance on a direction-discrimination task. Our data demonstrate that, by themselves, local cues can almost unambiguously indicate the facing direction of the agent in biological-motion stimuli. Additionally, we document a noteworthy interaction between local and global information and offer a new explanation for the effect of local inversion in biological-motion perception.

Keywords

motion perception, social perception, visual perception

Received 1/25/11; Revision accepted 6/8/11

Moving point lights attached to the major joints of a human or animal can give a vivid impression of the agent's action. This phenomenon is known as biological-motion perception (Johansson, 1973). Biological-motion displays consisting of only a few moving dots can convey a host of information about the features of a moving agent, such as its facing direction (Bertenthal & Pinto, 1994; Chang & Troje, 2009a; Mather, Radford, & West, 1992; Troje & Westhoff, 2006), gender (Barclay, Cutting, & Kozlowski, 1978; Kozlowski & Cutting, 1977; Mather & Murdoch, 1994; Pollick, Kay, Heim, & Stringer, 2005; Troje, 2002), emotion (Dittrich, Troscianko, Lea, & Morgan, 1996; Pollick, Paterson, Bruderlin, & Sanford, 2001), and identity (Cutting & Kozlowski, 1977; Troje, Westhoff, & Lavrov, 2005).

The phenomenology of biological-motion perception can in large part be explained by the impressive ability of the human visual system to perceptually organize the individual moving dots in a point-light display into the coherent shape of an articulated body. A wealth of literature has been dedicated to exploring the role of motion in that process. When the dots in a point-light display move with the joints of the agent's

body, observers may use interpretations based on local rigidities in the movements of small subsets of two or three dots to define articulations (Hoffman & Flinchbaugh, 1982). However, the human visual system seems to be versatile enough to retrieve the structure of the body even when the dots do not represent joint locations but are instead positioned at random locations on the body, although this process takes more time and is less accurate (Cutting, 1981). Structure can be retrieved even when dot locations change randomly from frame to frame (Beintema & Lappe, 2002). The presence of a pronounced inversion effect in biological-motion perception, similar to the inversion effect found for the configural processing of human faces (see Farah, Tanaka, & Drain, 1995, for a review), also seems to suggest that the recovery of global shape and articulated kinematics plays a key role in biological-motion

Corresponding Author:

Nikolaus F. Troje, Queen's University, 62 Arch St., Kingston K7L 3N6, Ontario, Canada

E-mail: troje@queensu.ca

perception (Bertenthal & Pinto, 1994; Pavlova & Sokolov, 2000; Sumi, 1984; Troje, 2002).

However, important information is contained not only in global shape and global motion, but also in the local motion of individual dots. Point-light displays of sagittally presented, stationary (as if on a treadmill) walkers that are fully scrambled with respect to spatial location and relative phase of the dots still contain ample information about the walker's facing direction. In a direction-discrimination task using such displays, naive observers responded with about 80% accuracy, even though the agent was embedded in a mask of flickering dots (Troje & Westhoff, 2006). However, observers could not make use of information contained in the local motion of individual dots if the stimulus was turned upside down. Further investigation revealed that the local motion of the dots representing the feet acted as the only cue to facing direction and entirely accounted for the observed inversion effects.

This result has been replicated and extended in a number of studies (Chang & Troje, 2008, 2009a; Saunders, Suchan, & Troje, 2009; Shi, Weng, He, & Jiang, 2010; Thompson, Hansen, Hess, & Troje, 2007). In a prior study (Chang & Troje, 2008), we showed that the inversion of scrambled point-light displays not only affects observers' ability to retrieve direction, but also decreases the perceived animacy of the stimulus. When we further investigated the local invariant that drives the discrimination of facing direction and the perception of animacy in scrambled biological-motion displays, we found that observed inversion effects were due to signatures in the vertical acceleration pattern of the feet, a pattern that is shaped by both gravitational and biomechanical constraints (Cavagna, Heglund, & Taylor, 1977).

Of course, signals contained in the vertical motion of the feet cannot provide information pertaining to the walker's horizontal direction or orientation—only horizontal asymmetries can. Horizontal asymmetries, however, retain the same degree of asymmetry when they are flipped upside down, and thus should not cause inversion effects. So, how can the observed inversion effects be explained? The trajectory of each foot of a stationary walker is closed and repeats itself periodically. The direction along which the trajectory is traced is characterized by a strong directional asymmetry. Even though the trajectory of each foot by no means follows a perfect circle, its movement is either clockwise or counterclockwise, just as a point on the rim of a rolling wheel describes either a clockwise or a counterclockwise movement. In the case of a rolling wheel, clockwise motion would indicate rightward movement, and counterclockwise motion would indicate leftward movement. Observers would interpret the wheel's movement in such ways on the basis of the assumption that the wheel should be rolling on the ground rather than magically adhering to the ceiling. (Note that the *rolling-wheel cue* is not the only asymmetry in the movement of point-light walkers. We consider other cues in the General Discussion section.)

Whatever information is used by observers is present in the inverted stimulus to the same degree that it is present in the

upright stimulus. Whether or not information is used by the observer, however, seems to depend on other cues that do not themselves contain any information about facing direction but rather validate the horizontal cues to direction and, possibly, label the whole stimulus as animate and "biological." In prior work (Chang & Troje, 2009a; Troje & Chang, in press), we found that one such validating cue is the vertical velocity profile of the feet and whether it is consistent with the direction of gravity.

However, vertical acceleration may not be the only validating cue. Shipley (2003) noted the possibility of an interaction between cues to global shape and local motion. He presented observers with upright and inverted versions of a point-light display created from motion captured from a person walking on his hands and found that observers detected the presence of point-light figures better when the figures were in upright displays than when the displays were inverted. That is, observers' accuracy benefited from a condition in which the orientation of the articulated body was inverted but the walking motion itself (executed by the hands) occurred on the ground below the rest of the body, where the chief movements involved in walking usually occur.

In the research reported here, we investigated whether the location of the dots representing the feet relative to the other dots in point-light displays plays a role in validating the cues to direction contained in the local motion of the feet. Observers' sensitivity to horizontal facing direction may be significantly affected by whether this information is conveyed by dots at the bottom of the display, where observers expect the feet to be, or by dots in unexpected locations.

To test this hypothesis, we designed point-light stimuli that avoided any confounds with directional cues contained in the shape of a coherent, nonscrambled walker. All stimuli used in this study were scrambled horizontally, and both the vertical position of the individual trajectories and their local orientation were manipulated in a systematic way. Our stimuli thus did not contain any structural information that observers could use to determine facing direction. The local motion of the individual dots was the only directional information contained in the displays. This information was present in all of our stimuli; we predicted that its validation and use by observers would depend on two factors: (a) whether the trajectories were locally upright or inverted, and (b) whether the trajectories representing the feet were below or above the rest of the dots in the display.

Experiment 1

Method

Participants. Twelve observers (ages 18 to 26 years, $M = 21.4$ years; 6 males, 6 females) took part in Experiment 1. All observers had normal or corrected-to-normal vision and received monetary compensation for their participation. Informed consent was obtained from all participants.

Stimuli. Stimuli were derived from point-light sequences of a walking human. The walker was a composite created from motion-captured data of 50 men and 50 women (Troje, 2002, 2008) and was depicted by a set of 11 markers located at the head, one shoulder, one hip, two elbows, two wrists, two knees, and two ankles, respectively. The translating component of the walking was removed so that the walking figures were stationary. All walkers were presented in profile, facing either to the left or to the right, and had a stride frequency of 0.93 Hz.

All of the stimuli used in Experiment 1 were scrambled with respect to the horizontal position of the individual dot trajectories. We achieved this horizontal scrambling by discarding the horizontal position of each trajectory and replacing it with a random horizontal position sampled from a uniform distribution with a width of 3° of visual angle, which is about the normal range of horizontal positions for the coherent walker. In addition, we temporally scrambled the walker in each display by assigning each of the 11 dots an independent, random starting phase.

All stimuli were derived from these horizontally scrambled and phase-scrambled walkers according to a 3×2 factorial design. The first factor was global organization, the vertical location of the individual dots (upright, inverted, or scrambled). In globally upright displays, the vertical position of the trajectories remained normal: The dots representing the walkers' feet were at the bottoms of the displays and the dots representing the walkers' heads were at the top. In globally inverted displays, the locations of these dots were reversed, and in globally scrambled displays, the vertical locations of the dots were chosen randomly. The second factor was the orientation of the individual trajectories (upright or inverted). In locally inverted displays, each individual dot trajectory was flipped about a horizontal axis that passed through the mean location of that particular dot.

Stimuli were generated using MATLAB (The MathWorks, Natick, MA) with extensions from the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) and were displayed on a 17-in. CRT color monitor (Samsung SyncMaster 735DF) with a spatial resolution of 1024×768 pixels and a frame rate of 85 Hz. All stimuli appeared as white dots on a black background. The full point-light figures subtended visual angles of $3.1^\circ \times 5.7^\circ$.

All point-light displays were embedded in a flickering mask that consisted of 100 randomly positioned, stationary dots. After a lifetime of 170 ms, each dot disappeared from its current location and was replaced with a dot at a new location. The mask subtended an area of $10.6^\circ \times 10.6^\circ$.

Each stimulus was displayed on-screen for 2 s, after which the observer was prompted to respond.

An interactive animation illustrating the stimuli used in this experiment can be viewed online at <http://biomotionlab.ca/Demos/BMLlocal.swf>.

Procedure. Participants were seated in front of the CRT monitor at a viewing distance of 48 cm. They were told that they

would see a number of point-light displays masked with a cluster of flickering dots and that their task was to indicate the facing direction of the walker in each display. Participants responded by pressing the left or right arrow key of a computer keyboard. After they were given instructions, participants completed 16 practice trials. The first 4 practice trials showed unmasked, intact (i.e., unscrambled), upright walkers facing either to the left or to the right. The next 6 trials showed unmasked visual stimuli for all experimental conditions. The last 6 practice trials showed masked visual stimuli for all experimental conditions.

Participants were then tested in three blocks. In each block, all combinations of the two facing directions of the walker (left or right), the three global organizations (upright, inverted, or scrambled), and the two orientations of local motion (upright or inverted) were presented six times in random order, for a total of 72 trials per block and 216 trials in all.

Results and discussion

Overall, the mean level of accuracy was 59.3%. An analysis of variance did not reveal an effect of global organization, $F(2, 22) = 1.4$, n.s., but showed a highly significant effect of local orientation, $F(1, 11) = 43.2$, $p < .001$, $\eta_p^2 = .80$, and an interaction between the two factors, $F(2, 22) = 57.4$, $p < .001$, $\eta_p^2 = .84$.

In the globally upright and globally scrambled conditions, observers' accuracy decreased when the local trajectories of displays were inverted (Fig. 1a). However, the degree to which accuracy decreased strongly depended on the global organization of the stimulus. On globally upright trials, in which the walker was presented with its feet located in their familiar position below the rest of the body, the effect of local inversion was strong: The level of performance was high for locally upright walkers but was significantly below chance for locally inverted walkers; in the globally upright, locally inverted condition, the perceived facing direction of the walker was therefore reversed. Note, however, that the reversal was not complete. When local motion was upright, observers indicated the facing direction of the walker with 91.9% accuracy. However, when local motion was inverted, only 75.5% of the responses indicated the incorrect facing direction. The overall level of accuracy in the globally upright condition was therefore 58.2%, clearly above chance level, $t(11) = 4.14$, $p < .01$.

When the global organization of the stimulus was inverted so that the walker's feet were located at the top of the display, differences between the two local-motion conditions were virtually eliminated. Overall accuracy in the globally inverted conditions was relatively low, but still above chance level at 57.8%, $t(11) = 2.56$, $p < .05$. When the vertical location of the trajectories was scrambled, the effect of local inversion was about midway between the effects of local inversion observed in the two other conditions. The overall level of accuracy for the globally scrambled conditions was 62.0%; responses for upright local trajectories were 78.4% correct, and performance for inverted local trajectories was just below chance level.

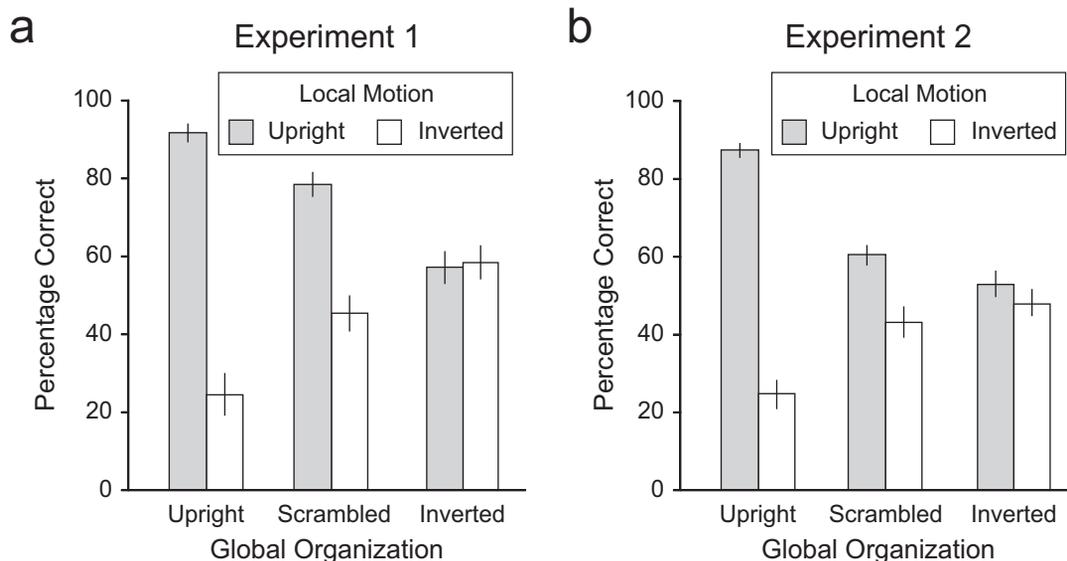


Fig. 1. Results from (a) Experiment 1 and (b) Experiment 2: average percentage of accurate responses as a function of global organization and local orientation of the point-light walkers. Error bars indicate standard errors of the mean.

Note that for spatially scrambled walkers, the local inversion of all of the individual trajectories was equivalent to the global inversion of the whole stimulus. The stimuli in the globally scrambled conditions are therefore equivalent to the upright and inverted scrambled biological-motion stimuli used in earlier studies (e.g., Troje & Westhoff, 2006). Unsurprisingly, the results in the present study are very similar to the results from these earlier studies with similar conditions. The present data, however, contribute important information about the inversion effect for scrambled biological motion. Our interpretation is as follows.

The horizontal asymmetry that serves as the observer's main cue to the facing direction of a walker without any articulated body structure is in fact the rolling-wheel cue contained in the circular trajectory of the feet. To be used by the observer, however, this cue requires validation. We note two sources of such validation. One source has been extensively described in previous research (Chang & Troje, 2008, 2009a; Troje & Chang, in press): the vertical velocity profile of the motion of the feet and whether or not such motion is consistent with the direction of gravity.

The other source of validation is derived from the location of the dots that feature the rolling-wheel cue and whether or not their location is consistent with the fact that feet are usually close to the ground. In the globally upright, locally upright condition, even though no structural cues with which observers could determine facing direction were available, observers achieved a high level of accuracy, with error rates of only about 8%. In this condition, both vertical acceleration and location validated the directional cue. In the globally upright, locally inverted condition, validation was still relatively strong because the feet were in their expected location, but not quite as strong as in the globally upright, locally upright condition

because the pattern of vertical acceleration was no longer consistent with gravity. In the globally upright, locally inverted condition, observers trusted the rolling-wheel cue, which now indicated the incorrect facing direction, on 75.5% of trials. In the globally scrambled condition, the vertical location of the feet was random. We could not conduct a trial-by-trial analysis of performance in this condition because we did not keep track of the randomized vertical locations of the feet, but we assume that observers' mediocre performance in the globally scrambled, locally upright condition was due to the mixture of trials in which the feet happened to be low in the display with trials in which the feet happened to be high in the display.

In the globally scrambled, locally inverted condition, performance was just below chance level, a result consistent with our previous findings (Troje & Westhoff, 2006). In this condition, the rolling-wheel cue indicated the wrong facing direction but was not validated by the pattern of acceleration. However, if the feet happened to be positioned at their expected location at the bottom of the display, the stimulus might obtain moderate validation. As in the locally upright conditions, in the locally inverted conditions, the level of performance in the globally scrambled condition was midway between the level of performance in the globally upright condition and that in the globally inverted condition.

Experiment 2

In Experiment 1, all trials appeared in random order. Consciously or unconsciously, observers may have searched at the bottom of the displays for the dots that represented the walker's feet and found those dots more reliably on globally upright trials than on globally inverted or globally scrambled trials for that reason. This possibility could potentially account for the

observed interaction between global organization and local orientation.

On the basis of our experience in prior studies with naive observers and the feedback we obtained from them, we deem this possibility rather unlikely. Nevertheless, we designed Experiment 2 to investigate whether performance on the experimental task in Experiment 1 was affected by the unpredictability of the location of the feet. In Experiment 2, rather than presenting all trials in random order, we divided each session into distinct blocks, one for each of the three types of global organization.

Method

Twelve new observers (ages 20 to 30 years, $M = 22.1$ years; 2 males, 10 females) participated in Experiment 2. All of them had normal or corrected-to-normal vision and received monetary compensation for their participation.

The stimuli and apparatus were identical to those in Experiment 1. Observers were again tested in three sessions of 72 trials each. The only change in procedure with respect to Experiment 1 was that in Experiment 2, one block consisted of only globally upright trials, a second block consisted of only globally inverted trials, and a third block consisted of only globally scrambled trials. Each of the six possible orders of the three blocks was used twice across the 12 participants.

Results and discussion

The results of Experiment 2 (Fig. 1b) were similar to those obtained in Experiment 1. We found the same effects of local orientation, $F(1, 11) = 43.2$, $p < .001$, $\eta_p^2 = .80$, and again found an interaction between local orientation and global organization, $F(2, 22) = 43.7$, $p < .001$, $\eta_p^2 = .80$. The main difference between the results of the two experiments is that the level of overall performance on globally inverted and globally scrambled trials was somewhat reduced in Experiment 2. Overall performance in the globally upright condition in Experiment 2 was about the same as it was in Experiment 1. The difference in overall performance among the three global-organization conditions resulted in a small main effect, $F(2, 22) = 6.0$, $p < .05$, $\eta_p^2 = .35$. We conjecture that at least some of the participants felt that they had no hope of performing the task well and gave up in the globally inverted and globally scrambled blocks of Experiment 2. If the trials in those blocks had been intermixed with easier trials (as they were in Experiment 1), participants might have maintained their motivation to respond accurately even if individual trials seemed impossible to solve.

Critically, the noteworthy effects observed in Experiment 1 were replicated in Experiment 2 even though the location of the feet was predictable in the globally upright and globally inverted conditions. Thus, although the rolling-wheel movement determines the perceived facing direction when the feet are at the bottom of the display, the same trajectories are not

used to determine direction when the feet are located at the top of the display.

General Discussion

Our data are consistent with the hypothesis that the main directional cue contained in the local motion of the feet in point-light biological-motion displays is the rolling-wheel cue, that is, the direction in which the dots representing the feet track their trajectories. As in the case of a point on the rim of a wheel rolling on the ground, a clockwise trajectory indicates rightward motion, and a counterclockwise trajectory indicates leftward motion. However, the information contained in this cue is used by observers only when it is combined with additional validating cues that do not themselves contain information about the walker's direction. Although we have shown previously that the vertical velocity profile of the feet plays an important role in that respect, the present results demonstrate that the role of the vertical location of the dots carrying directional information within the display is at least as significant.

As we mentioned at the beginning of the article, the direction of the rolling-wheel motion is not the only horizontal asymmetry that can be derived from the trajectories of the feet. Another cue that could potentially indicate direction is the difference between the kinematics of the stance phase (constant horizontal velocity) and the swing phase (varying velocity with a higher peak velocity) of the feet. Using this cue, observers could determine the walker's facing direction on the basis of the horizontal movement of the dots representing the feet during the varying velocity phases (Chang & Troje, 2009a). Note, however, that the rolling-wheel cue and the asymmetry in the horizontal velocity would be affected differently by inversion. When the stimulus is flipped about a horizontal axis, the spinning direction of the rolling-wheel motion reverses. In this case, a right-facing walker would be perceived as facing left, and vice versa. In contrast, the perceived facing direction as determined by differences in the velocity profiles of the stance and swing phases would not be reversed upon inversion. Our finding of a pronounced perceptual reversal caused by local inversions provides strong evidence for the importance of the rolling-wheel cue in inversion effects and evidence against the role of other asymmetries that would not indicate a reversed direction when inverted.

Our findings in this study blur the traditional distinction between the roles of global and local information that dominates much of the recent literature on biological-motion perception. The vertical location of the dots representing the feet relative to the rest of the body clearly has to be considered global, configural information. Although it does not provide any information about the facing direction of a walker, it strongly interacts with the entirely local rolling-wheel cue. As has been shown for the relevant signatures in the vertical velocity profile (Chang & Troje, 2008), validation may be conveyed through a general increase in the perception of

animacy and agency: Observers assign a facing direction to a stimulus only if they determine it to be animate.

The invariant that results from the integration of directional cues and validating modifications shares some characteristics with Ullman's (1984) "visual routines," Casile and Giese's (2005) "mid-level features," and the concept of "motion sprites" introduced by Cavanagh, Labianca, and Thornton (2001). However, although some of these concepts are associated with attentional processes and individual learning (Thornton, Rensink, & Shiffrar, 2002), we think that the mechanisms implicated by the results of our study are not susceptible to learning (Chang & Troje, 2009b) and that they guide attention rather than requiring it (Hirai, Saunders, & Troje, 2011).

The visual filters that determine whether vertical acceleration is consistent with the orientation of gravitational acceleration and that assign animacy to visual motion are likely to be evolutionarily old, possibly even older than the mammalian cortex (Vallortigara, Regolin, & Marconato, 2005), and seem already to be present in human neonates at birth (Bardi, Regolin, & Simion, 2011; Simion, Regolin, & Bulf, 2008). Newly hatched chicks not only display a preference for intact foot motion but also respond to its indicated direction, a result that suggests that they also use the rolling-wheel cue (Vallortigara & Regolin, 2006). It is not yet clear whether the mechanisms that evaluate the vertical location of the diagnostic local movements within a biological-motion display are just as old, but the fact that vertical location retained its strong effect even under the conditions of Experiment 2 provides some hints. Apparently, the role of the location of the feet does not arise simply from learned expectations or attentional effects. The location of the feet was as predictable in the globally inverted condition of Experiment 2 as it was in the globally upright condition, but observers did not make use of the information contained in the local motion of the feet.

This explanation leads to a new perspective on inversion effects in general. Inversion effects are commonly believed to stem from inabilities of a visual mechanism to interpret a visual signal presented in an unusual orientation. Our observations, however, suggest the alternative possibility that inversion effects are in fact the product of adaptive mechanisms. There may be good reasons why the visual system ignores certain cues in one context but responds to them in another. The validation mechanisms suggested by our findings would certainly help to reduce the false alarms of a general "life detection" system that has to distinguish between biological and nonbiological motion.

Our findings provide an example of a strong interaction between global and local information and suggest that researchers should consider the role of these seemingly complementary domains from a new perspective.

Acknowledgments

The authors acknowledge the invaluable technical help provided by Stephen Scovil.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Funding

This work was supported by grants from the Japan Society for the Promotion of Science for Young Scientists to M. H. and by grants from the Natural Sciences and Engineering Research Council of Canada and from the Canadian Institute for Advanced Research to N. F. T.

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