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Strategies for active camouflage of motion

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SUMMARY

In this paper we consider whether an animal or an agent (a 'shadower') can actively camouflage its movements whilst tracking another animal or agent (a 'shadowee'). It is shown that, under certain conditions, the shadower can conceal its motion if it moves along a trajectory such that it emulates the optic flow produced by a stationary object, as viewed by the moving shadowee. Algorithms for determining trajectories which enable the shadower to camouflage its motion whilst tracking a shadowee, or whilst moving toward a stationary or moving target, are developed and tested. The proposed strategies work regardless of whether the shadower is viewed against a homogeneous or a structured background. It is of interest to investigate the relevance of active motion camouflage in contexts such as 'shadowing' behaviour in hoverflies, capture of prey by predators and military manoeuvres.

1. INTRODUCTION

As an animal or a robot moves, the images of the objects in the environment move on the retina (or on the imaging surface of the robot's camera), even if the objects are physically stationary in the environment. Nevertheless, some animals (Cott 1966) including insects (Lehrer & Srinivasan 1992) are adept at distinguishing between stationary and moving objects, when they themselves are in motion. Usually, the optic flow produced by a self-moving object is inconsistent with that produced by a stationary one (Gibson 1950). Evidently, the visual systems of many animals are capable of detecting this inconsistency, but this poses the question: how can one animal (or agent) track, or 'shadow' another without giving itself away by its own motion?

A lioness approaching its prey (Cott 1966; Curio 1976) or an amorous male praying mantis approaching a potential mate (Roeder 1967) uses a simple but effective ploy: that of moving very slowly. Stealth, however, is feasible only when the prey or mate is stationary; it is not an option when the prey is moving rapidly away from the predator. Here we are concerned with the question of how a shadower might conceal its motion actively during pursuit. To our knowledge, the problem of active motion camouflage has not been considered previously.

2. MOVING WHILST MINIMIZING APPARENT MOTION

We assume that the shadower is far enough away from the shadowee that it can be approximated by a point object, from the shadowee's viewpoint. This also implies that movements of the shadower's limbs (or wheels) are not resolvable, i.e. to the shadowee the shadower appears as a structureless dot. We also assume that, at the distances involved, stereoscopic and looming cues are so weak that the shadower cannot detect changes in range of the shadowee.

Under these conditions, the shadower can conceal its motion by moving in such a way that it produces the same image motion on the shadowee's retina as would a stationary object in the environment. In figure 1*a*, suppose the shadower (A) wishes to track a moving shadowee (B) by imitating a stationary object at the point F (the 'fixed point'). The shadower can accomplish this by moving in such a way that it is always on a straight line connecting the shadowee to the fixed point, as illustrated in the figure. We term this line the 'camouflage constraint line'. The apparent motion of the shadower's image on the retina or camera of the shadowee would then be exactly the same as that produced by a stationary object at the fixed point.

There are, of course, an infinite number of possible trajectories for the shadower that would satisfy this requirement because at each instant of time the shadower can occupy any position along the camouflage constraint line corresponding to that instant. Furthermore, the fixed point can be chosen to be anywhere along the initial camouflage constraint line (the line joining the initial positions of the shadower and the shadowee). Trajectories resulting from four different choices of the fixed point are illustrated in figure 1. If the fixed point is chosen to be behind the shadower, the shadower would have to move along paths of the kind shown in figure 1*a*. If the fixed point is chosen to be in front of the shadower, the shadower's trajectory would have to be of the form shown in figure 1*b*. A frontally placed fixed point would not be useful for approaching the shadowee, but it can be used if the

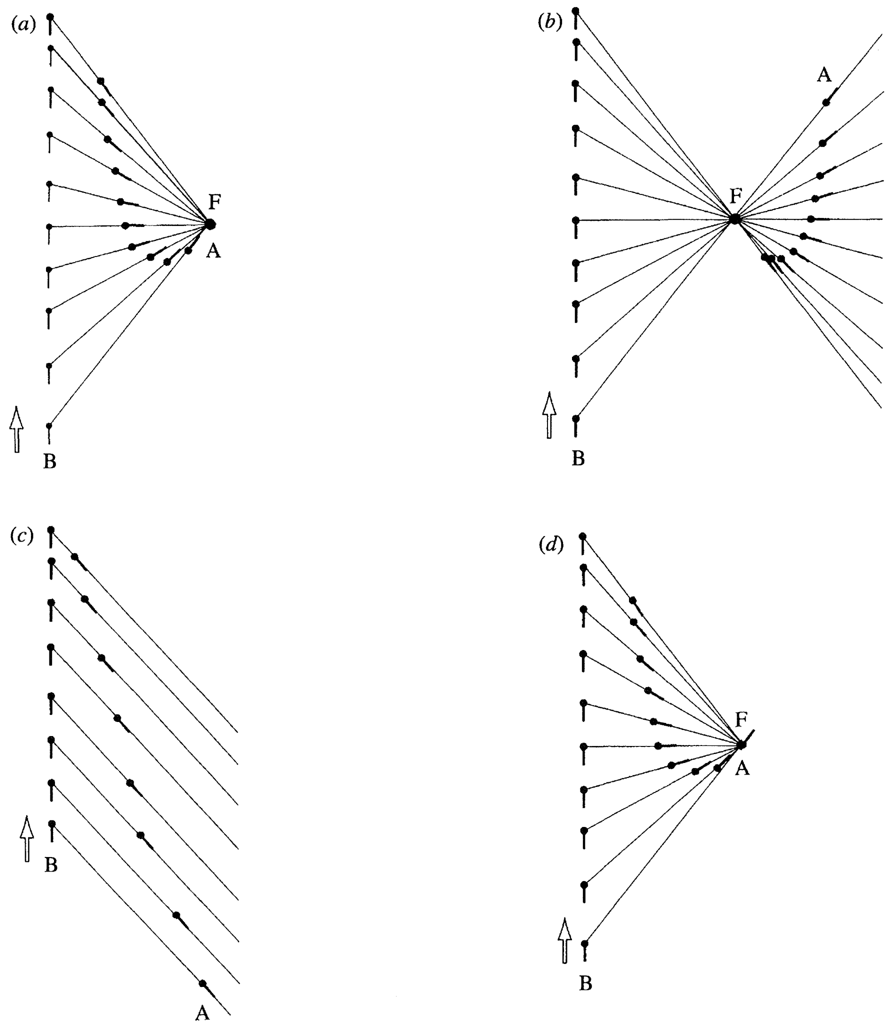

Figure 1. Trajectories of a shadower (A) and a shadowee (B), showing positions at regular time intervals. A can camouflage its motion by emulating a stationary object at a point F which is (*a*) behind it, (*b*) in front of it, (*c*) at infinity, or (*d*) located at A's initial position.

shadowee simply wishes to move from one location to another whilst camouflaging its motion. The fixed point can also be an infinite distance away, as illustrated by the example of figure 1*c*: the shadower would then emulate an object at infinity. The most natural form of motion camouflage, however, is obtained when the fixed point is chosen to be at the shadower's initial location (see figure 1*d*). This avoids any abrupt change in the shadower's apparent position at the start of the shadowing process.

It is important to note that the strategy described above will work regardless of whether the shadowee views the shadower against a background that is homogeneous or structured. If the background is structured, the image of the shadower may move relative to that of the background – producing motion parallax – but this parallax would be identical to that produced by a stationary object at the fixed point.

How might a shadower determine trajectories which can camouflage its motion?

Computationally, two algorithms seem possible. First, the shadower could simply choose a visible landmark, for example on the ground, and use this as the fixed point. The shadower could then remain on the camouflage constraint line by continually positioning itself on the straight line connecting the landmark to the shadowee. By doing so the shadower would create the impression that it is stationary and situated at the landmark. However, this requires the presence of a suitably located landmark, which may not always be feasible, especially in terrain where landmarks are scarce.

The second algorithm dispenses with the requirement of a landmark and can be described as follows. Assume, for simplicity's sake, that the fixed point is to be located at the shadower's initial position. The shadower can ensure that it remains on the camouflage constraint line by: (i) always viewing the shadowee frontally; and (ii) always pointing radially away from its starting point. To accomplish this, the shadower would have to know its instantaneous distance from the fixed point. It can then maintain the shadowee's image in its frontal field of view by making corrective yaws, $\Delta\theta$, and corrective lateral motions, $\Delta\lambda$ such that the magnitudes of the two corrections are related by $(\Delta\lambda/\Delta\theta) = \rho$, where ρ is the shadower's current distance from the fixed point (see figure 2*a*). This requires that the shadower 'know' its distance ρ from the fixed point, and adjust the relative amounts of corrective yaw and sideslip such that the farther away

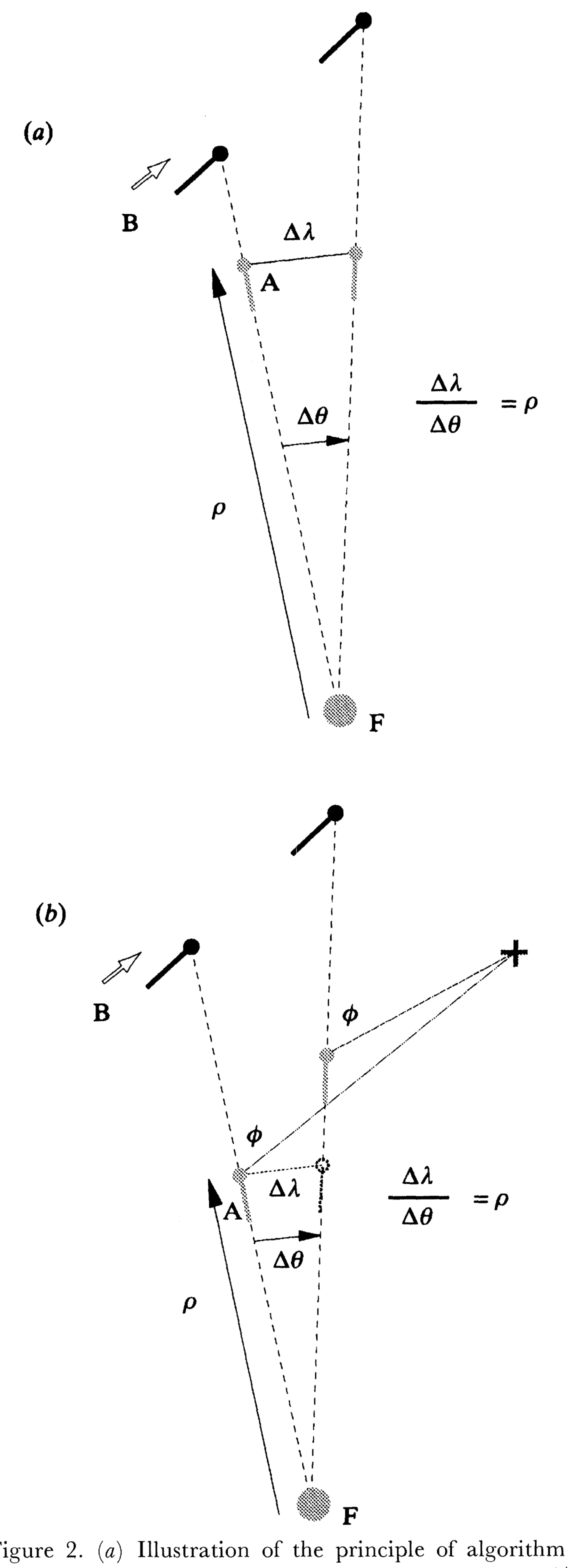

Figure 2. (*a*) Illustration of the principle of algorithm 2, showing the relation required between corrective yaw ($\Delta\theta$) and corrective lateral movement ($\Delta\lambda$) if a shadower (A) is to emulate a stationary object at F whilst tracking a shadowee (B). (*b*) Illustration of algorithm 3, which enables a shadower (A) to emulate a stationary object at F, as in (*a*), and to reach a target (+). Here the shadower follows the same rule as in algorithm 2 and, in addition, moves along the constraint line so as to hold the bearing of the target constant.

the fixed point, the larger the ratio of sideslip correction to yaw correction. This can be achieved by coupling yaw to sideslip and varying the coefficient of coupling according to distance. The radial component of the shadower's motion (the motion toward or away from the shadowee) is not constrained in any way; the shadower can approach the shadowee, retreat from it or maintain a constant distance from it. In addition, the radial speed can be chosen or varied to avoid obstacles, or to pass through specific locations en route. Furthermore, the fixed point does not necessarily have to be placed at the shadower's starting location, it can be placed at any desired distance d from it (but, of course, on the initial camouflage constraint line) by setting the initial value of ρ equal to d in the computation; d can be positive (corresponding to a fixed point behind the shadower) or negative (corresponding to a fixed point in front).

So far, we have placed no constraints on the shadower's speed. If, however, the shadower's radial speed (or total speed) is specified to be some constant value, then the shadower's trajectory is completely determined by the shadowee's motion and the choice of fixed point. The only freedom in the shadower's motion is then in deciding whether to approach or retreat.

Two simulations of the second algorithm are shown in figure 3. In the example of figure 3*a* we have assumed that the fixed point F is located at the shadower's initial position, and considered a situation in which the shadowee moves at constant velocity. The shadower's radial speed is held constant at 0.1 units per time step. It is clear that, at every instant of time, the shadower is on the appropriate camouflage constraint line, thus maintaining perfect motion camouflage.

Neither the linearity of the shadowee's trajectory, nor the constancy of the shadowee's speed, nor the location of the fixed point is crucial to the operation of either of the algorithms described above. For example, figure 3*b* illustrates the performance of algorithm 2 in a situation in which the shadowee moves along a curve at variable speed and the fixed point is behind the shadower's starting location: the shadower again maintains perfect motion camouflage. If the shadowee ceases to move, both algorithms dictate that the shadower simply moves along the (now) stationary camouflage constraint line.

It is important to emphasize that algorithm 2 does not use the fixed point as a landmark. It does not carry any explicit representation of the fixed point's location in two-dimensional space; it only requires that the shadower be able to keep track of its distance from the fixed point. Once this distance is known, the shadower can ensure that it remains on the camouflage constraint line simply by controlling its sideslip so that the shadowee is always viewed frontally and, whilst doing so, adjusting the coupling between sideslip and yaw according to distance.

How can the distance to the fixed point be monitored? In the case of a mobile vehicle or robot, this can be done odometrically. With animals, there is now evidence that gerbils (Mittelstaedt & Mittelstaedt 1980), hamsters (Etienne *et al.* 1986), rats (Potegal 1987), fiddler crabs (Hagen 1967), spiders (Seyfarth *et al.* 1982) and some species of ants (for a review, see Wehner 1992) can use various forms of dead-reckoning

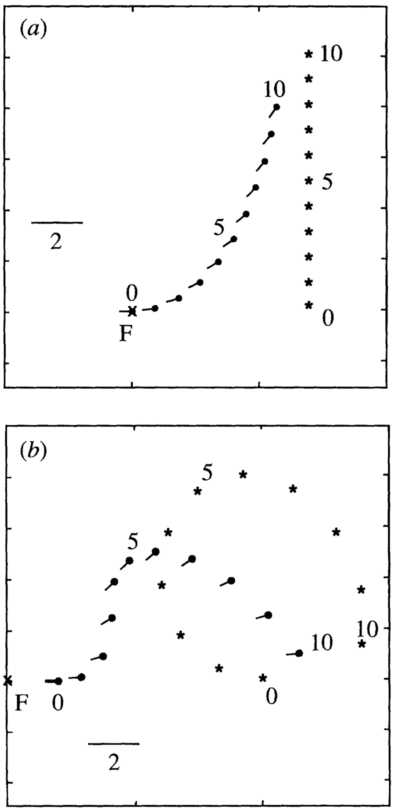

Figure 3. Two examples illustrating the performance of algorithm 2 for motion camouflage. In each case the shadower (circles with tails) tracks the shadowee (asterisks) and camouflages its motion by emulating a stationary object ('fixed point') at F. Positions of the shadower and the shadowee are shown at every tenth time step, and the numbers denote corresponding instants of time. In (*a*) the shadowee moves at constant speed along a straight line and the fixed point is at the shadower's initial position. In (*b*) the shadowee moves at variable speed along a curve and the fixed point is 2 distance units behind the shadower's initial location. In each case, the shadower's radial speed is chosen to be 0.1 distance units per time step. In both cases the shadower achieves perfect motion camouflage. Scale bars in figures 3 and 4 depict a distance of 2 units.

to establish how far they have travelled from their burrow or nest. Depending upon the species, this seems to be accomplished by integrating motor commands, proprioceptive signals, vestibular signals, or optic flow. A striking display of dead-reckoning is provided by the Saharan desert ant *Cataglyphis*, which forages over distances of as much as 250 m without laying any pheromone trails. As soon as it finds food it makes a 'bee line' back to the nest, even in terrain that is completely devoid of landmarks (Mueller & Wehner 1988). Several experiments have demonstrated conclusively that, at every stage of the searching phase of the foraging run, *Cataglyphis* is aware of the direction of and the distance to the nest, and that it acquires this information by continuously integrating its motions (for a review, see Wehner 1992). We note that the information required by algorithm 2 is less than what the dead-reckoning system of *Cataglyphis* is actually capable of providing. Here we only require knowledge of the distance from the starting point and not the bearing.

3. MOTION CAMOUFLAGE WHILST MOVING TOWARD A TARGET

An interesting variant of the shadowing problem is one in which the so-called shadower does not want to track or intercept the shadowee. Instead, the shadower wishes to move from its present location F (which is treated as a fixed point) to a target location (+) as illustrated in figure 4, and to do so without allowing its motion to be detected by the shadowee. The shadower can see the target, but does not know how far away it is; can this be accomplished, and if so, how?

Motion camouflage dictates that the shadower be constrained to move such that it always lies on the camouflage constraint line (which, in this case, is the line connecting the instantaneous position of the shadowee to the location of the stationary object F that the shadower emulates). As before, the camouflage constraint can be achieved by using either of the algorithms described above. However, there is the additional requirement that the shadower must reach the target. To do this, the shadower must adjust its radial speed such that it has moved the correct distance away from F at the instant when the camouflage

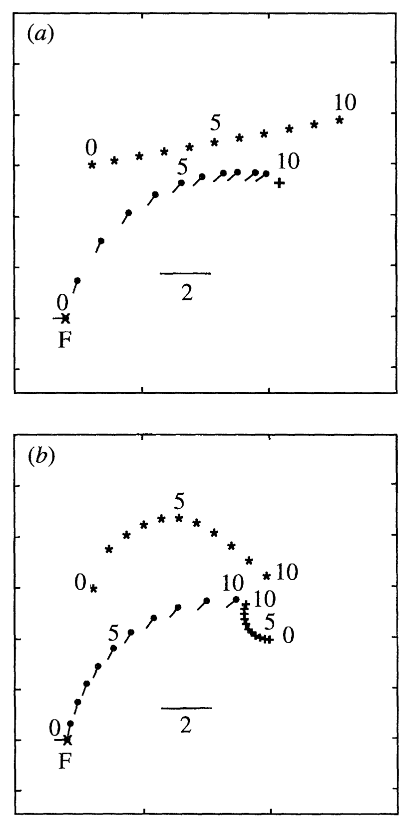

Figure 4. Two examples illustrating performance of algorithm 3 for motion camouflage, where the shadower (circles with tails) wishes to move to a target (+), simultaneously camouflaging its motion as seen by a shadowee (asterisks). In these examples the fixed point F is chosen to be at the shadower's initial location. Positions of the shadower and the shadowee are shown at every tenth time step, and the numbers denote corresponding instants of time. In (*a*) the shadowee moves along a straight line at constant speed, and the target is stationary. In (*b*) the shadowee moves along a curve at varying speed, as does the target. In both cases, the shadower achieves perfect motion camouflage.

constraint line passes through the target. If the radial speed is too low the shadower will undershoot the target, and if it is too high the shadower will overshoot. How can arrival at the target be ensured? A simple strategy would be for the shadower to adjust its position along the camouflage constraint line so that the bearing of the target relative to the shadower remains fixed at its initial value, as illustrated in figure 2*b*. Thus, in the example of figure 4*a*, as time evolves the shadower moves progressively outward along the motion constraint line, holding the bearing of the target constant. This procedure will ensure that the shadower arrives at the target. Of course, the target can be reached only if the shadowee's trajectory is such that it causes the camouflage constraint line to intersect the target at some instant of time. If this does not occur then obviously the problem has no solution.

We note that the third algorithm forces the shadower to move along the camouflage constraint line in such a way as to hold the target bearing constant. Because of this, the shadower does not necessarily reach the target via the shortest possible path, or in the shortest possible time after commencing the run. Optimal trajectories that meet such additional requirements can be calculated if the complete trajectory of the shadowee is known beforehand (or can be predicted reliably) and if the distance of the target from the shadower's starting point is known. We shall not pursue these questions here. The attractive feature of the present strategy, however, is that it does not require any prior knowledge. It works even when the speed and direction of motion of the shadowee vary unpredictably, or when the target is not stationary. The reason is that the strategy relies on instantaneous, 'on-line' control of the shadowers's motion, rather than on precomputed control based on a knowledge of the shadowee's entire trajectory. In the example of figure 4*b*, the shadowee moves along a curved path and the target is also in motion. Yet, the shadower is able to camouflage its motion and reach the target by employing the simple control algorithm described above.

In the examples of figure 4, the shadower commences its run toward the target at time $t = 0$, that is, when the shadowee is at its initial position. But this is not necessary: the shadower can wait for the shadowee to progress for some time, before starting. When the run is commenced, the shadower maintains the bearing of the target as seen at that instant. A longer wait will result in a more direct trajectory to the target, but the shadower will have to move faster when it eventually starts. The limiting case is to wait until the shadowee is in line with the target, and then to dash straight toward the target at infinite speed.

4. MOTION CAMOUFLAGE IN THE PRESENCE OF TWO SHADOWEES

Can a shadower camouflage its motion as seen by two moving shadowees? The answer is yes, as illustrated in figure 5. The shadower, initially located at 1*, wishes to camouflage its motion as seen by two shadowees. Shadowee A moves along the trajectory 1, 2, 3, ..., and shadowee B along the trajectory 1′, 2′, 3′... where the numbers denote corresponding instants of time. The shadower camouflages its motion as seen by shadowee A by emulating a fixed point at F_A, and its motion as seen by shadowee B by emulating a fixed point at F_B. The trajectory of the shadower is then determined by the locus of the intersection of the camouflage constraint lines associated with the two fixed points, at corresponding instants of time. In the example of figure 5, successive positions of the shadower are depicted by 1*, 2*, 3*.... How can the shadower determine the desired trajectory? Again, as in the above discussion, two approaches suggest themselves. First, the locations of the fixed points F_A and F_B could be chosen to correspond to two visible landmarks. The shadower would then move so that it places itself simultaneously on the lines connecting shadowee A to F_A, and shadowee B to F_B. Consider how the shadower, initially at 1*, should move when shadowee A has moved from 1 to 2, and shadowee B from 1′ to 2′. To maintain motion camouflage, the shadower should move from 1* to 2*. A simple way to accomplish this would be to execute the motion in two steps. The shadower first moves radially away from F_A until it lies on the camouflage constraint line for shadowee B, i.e. on the line connecting shadowee B to F_B. Then, the shadower moves radially away from F_B until it lies on the camouflage constraint line for shadowee A, i.e. on the line connecting shadowee A to F_A. The shadower will now be at the desired location 2*. Repetition of this two-step cycle will ensure that the shadower moves along the desired trajectory 1*, 2*, 3*.... If the shadower performs its corrective motions sufficiently rapidly, its zig-zagging motion will be small enough to be invisible to either shadowee. (As the speed of the shadower is increased, the shadower's motion will approach a smooth trajectory connecting the points 1*, 2*, 3*....) There are variants of this two-step procedure that eliminate the zig-zagging but we shall not describe them here.

If convenient landmarks are not available to set the locations of F_A and F_B, the fixed points would have to be chosen to lie at predetermined distances along their respective initial camouflage constraint lines. The shadower would then determine its motion relative to the fixed points as explained above, but by monitoring its motion through dead reckoning, rather than by

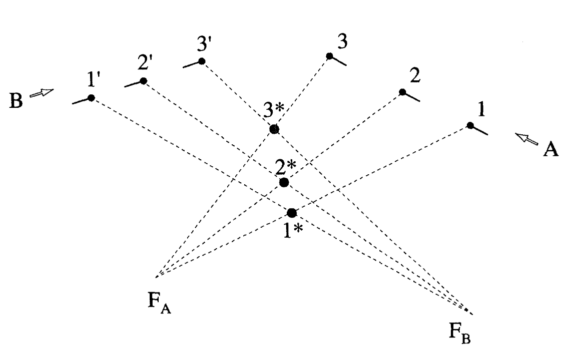

Figure 5. Trajectory of a shadower (1*, 2*, 3*...) which moves such that it simultaneously camouflages its motion as seen by two shadowees A and B, by emulating a stationary object F_A as seen by A, and another stationary object F_B as seen by B. For details see the text.

sighting landmarks. This, however, would require that the shadower possesses an idiothetic map that specifies its instantaneous location relative to the fixed points F_A and F_B.

In the two-shadowee problem, the choice of the locations of the fixed points is critical. Once these locations are chosen the motion of the shadower is completely constrained by the motion of the shadowees: there are no additional degrees of freedom. The locations of the fixed points and the shapes of the shadowees' trajectories will, therefore, determine whether the shadower can intercept one of the shadowees (for example), or arrive at a specified destination. Only one of the fixed points can be located at the shadower's starting location, 1* (if desired). The other fixed point cannot also be positioned at this location, because the camouflage constraint lines for the two shadowees would then always intersect at 1*, constraining the shadower to remain stationary.

From the above discussion, we see that the solution to the two-shadowee problem is a fully constrained one. It therefore follows that the solution to a three-shadowee problem is an overconstrained one that, in general, has no exact solution. However, at least in principle, there exists a solution that minimizes the shadower's motion as seen by the three shadowees.

Throughout this paper, we have implicitly assumed that the shadower and the shadowee move in a two-dimensional plane. Extension of these ideas to motion in three dimensions is fairly straightforward, although it is not pursued here. In the case of two shadowees, motion camouflage in three dimensions is possible only if the respective constraint lines intersect in 3-dimensional space.

5. RELEVANCE TO ANIMAL BEHAVIOUR

Do animals attempt to camouflage their motion whilst tracking each other? Whereas there are clear instances of animals minimizing their motion to escape detection, as mentioned in §1, we know of no definite evidence yet for active camouflage of motion. Certain flying insects, however, appear to be worthy of investigation in this context, e.g. the male hoverfly *Syritta pipiens* sometimes shadows females in flight. When a male spots a female he tracks her, maintaining a roughly constant distance from her by ensuring that her image subtends a constant vertical angle. When the female eventually lands, for example, on a flower, the male darts rapidly towards her to mate. This behaviour has been filmed and characterized elegantly by Collett & Land (1975, 1978), with the primary objective of understanding the mechanisms subserving the visual control of tracking. We have re-examined the flight trajectories that they have recorded, from a different point of view; that of motion camouflage. Two examples, taken from figure 28*a*, *d* of Collett & Land (1975), are shown in figure 6. In the example of figure 6*a*, the shadower moves in such a way as to emulate a stationary object behind it, located approximately at the circle. As the shadowee moves forward, the shadower yaws and moves laterally in such a way that it always stays on a line connecting the shadowee to the circle. In figure 6*b*, the shadower commences with the fixed point behind it but as the shadower backs away from the shadowee, the fixed point eventually appears in front of the shadower, requiring that the shadower's lateral motion now be in a direction opposite to what

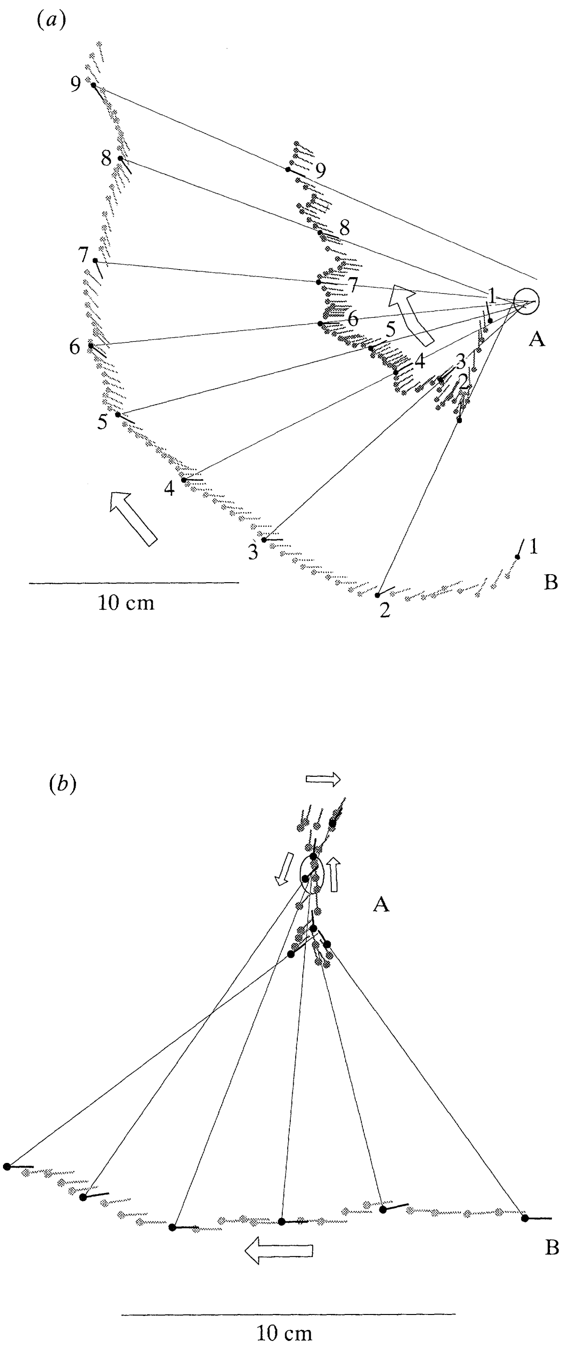

Figure 6. Two examples (*a*) and (*b*) of visually mediated interaction between hoverflies, *Syritta pipiens*, adapted from Collett & Land (1975). The positions of the flies are shown every 20 ms. Open arrows show direction of movement of fly A in each case. Straight lines are shown connecting the positions of the two flies at corresponding times (for clarity, these are shown for only every tenth frame in (*a*), and only every fifth frame in (*b*)). Most of the connecting lines intersect within a fairly compact region, as shown by the circle in (*a*) and the ellipse in (*b*). This is consistent with the notion that, in each case, fly A is shadowing fly B and camouflaging its motion by emulating a (quasi-) stationary object within the indicated region. For details see the text.

it was when the object was in the back. The shadower actually reverses its sideslip in this way, displaying a behaviour which is difficult to explain in terms other than motion camouflage.

Not all cases of shadowing, as documented by Collett & Land (1975), resemble the examples shown in figure 6. We have analysed several other shadowing episodes given in their paper, in the manner illustrated in figure 6. Often, a hoverfly will seem to place the fixed point at one location for the initial section of a shadowing episode and then move it to another, nearby location. Sometimes the fixed point is abruptly transferred to infinity, that is, the shadowing hoverfly no longer yaws but only moves laterally, emulating a distant (and presumably non-threatening) object. The beginning of such a transfer can be seen in the last section of the example of figure 6*a*.

Being relatively small, a shadowing hoverfly can be roughly approximated by a dot, at least in relation to the shadowee's visual acuity (Collett & Land 1975). Interestingly, hoverflies are able to control yaw and lateral motion independently, and flexibly (see, for a review, Collett *et al.* 1993). Thus it would appear that shadowing hoverflies not only have a strong incentive to camouflage their motion but they also possess the machinery to do so along the lines of algorithm 2. Further experiments are necessary, however, to determine whether these insects indeed practice active motion camouflage, or whether their behaviour during shadowing is just an illusory by-product of a control system that is intended primarily for tracking.

The last paragraph aside, we feel that the ideas described here are worth examining in relation to a variety of predatory animal species. It goes without saying that real-life interactions between predators and prey are likely to be complex, involving a variety of cues and tactics (Cott 1966; Curio 1976). Therefore, the strategies described here, based as they are on simplifying assumptions, may only apply under circumscribed conditions. In a broader context, the concept of active motion camouflage may be useful in developing new methods for concealment in military and security applications.

Although the motion-camouflage methods presented here cause the moving shadower to appear stationary to the shadowee, they are not entirely foolproof. If there are stationary objects present in the environment, then under certain conditions the movement of the shadower can be inferred if the shadowee observes the apparent motion of the shadower in relation to these other objects. For example, from the shadowee's point of view, a shadower emulating a fixed point at infinity (as in figure 1 *c*) will continue to occlude objects behind it. This, of course, cannot happen if the shadower is really at infinity.

The strategies introduced here for active motion camouflage can be extended in several ways. First, one can investigate trajectories that not only camouflage motion but are optimal in a specified sense, such as minimizing time to interception or distance travelled to interception. Second, strategies can be explored for camouflaging the motion of large objects which cannot be approximated by points. Third, one can ask what counter-strategies the shadowee could use to break the camouflage that the shadower is trying to create. In all these ventures, looking at the animal kingdom may provide unique insights (Hartcup 1979).

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