

## Opinion

## Timing decisions as the next frontier for collective intelligence

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The past decade has witnessed a growing interest in collective decision making, particularly the idea that groups can make more accurate decisions compared with individuals. However, nearly all research to date has focused on spatial decisions (e.g., food patches). Here, we highlight the equally important, but severely understudied, realm of temporal collective decision making (i.e., decisions about when to perform an action). We illustrate differences between temporal and spatial decisions, including the irreversibility of time, cost asymmetries, the speed–accuracy tradeoff, and game theoretic dynamics. Given these fundamental differences, temporal collective decision making likely requires different mechanisms to generate collective intelligence. Research focused on temporal decisions should lead to an expanded understanding of the adaptiveness and constraints of living in groups.

## Collective decisions in space and time

The idea that organisms might make more accurate decisions as a group than individually is an intriguing hypothesis that has received a substantial amount of research attention. This ‘wisdom of crowds’ comprises an important class of collective intelligence that can improve the fitness of individuals in the group [1]. Theoretical models have uncovered several mechanisms by which decision accuracy can be improved collectively, including a simple averaging of individual errors (e.g., the ‘many wrongs principle’) [2], context-dependent leadership or social learning [3], adjusting social network structure [4,5], and emergent sensing or collective learning (where the group can effectively perform a task or learn about a feature of the environment that individuals cannot perceive) [2,6]. Alongside this rapid progress in theoretical modeling, an increasing number of empirical studies has also revealed collective intelligence in real animals (e.g., [7–9]), and has also been a major focus in many human contexts [10], including team performance [11], medical diagnoses [12,13], and the design of artificial intelligence (AI) algorithms [14].

Importantly, however, the bulk of this work has focused, either explicitly or implicitly, on spatial decisions. In other words, most models and experiments study situations in which animals in groups decide where to go. In some studies, the directness of a trajectory to the goal location is the primary measure of performance (e.g., [15,16]). In others, animals in groups must decide between discrete locations in space, such as food patches (e.g., [17–19]), nest sites [20,21], or to avoid a potential predator (e.g., [9,22]). Many theoretical models are abstract and simply consider a number of discrete options (e.g., [23–25]) or a continuous space of options [10,26] without explicit reference to space, but these too can be mapped onto spatial decision tasks as discrete locations and directions of travel, respectively. Therefore, much of our current intuition of collective decision making has effectively been derived from studies of spatial decisions.

## Highlights

The fitness of an organism can be strongly affected by the decisions that it makes throughout its lifetime. These decisions may be spatial (deciding where to go), temporal (deciding when to perform an action), or a mixture thereof.

How organisms make spatial or temporal decisions should involve different mechanisms because of fundamental differences between the two. For example, time is irreversible, while animals can traverse space more freely.

Making decisions together as a group can improve the accuracy of decisions (a form of collective intelligence). However, to date, almost all existing research has been on collective spatial decisions and, as a result, it is through this spatial lens that our intuition of collective decisions has developed.

Understanding how individuals in groups make timing decisions is particularly relevant in a changing climate, where both the optimal time to perform actions and the cues used to time the action are changing.

Studying collective intelligence in the context of timing decisions will reveal novel mechanisms that social animals across taxa (including humans) use, allowing us to predict the future of species in a changing world and to design new bio-inspired strategies.

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By contrast, temporal decision making (when to perform an action) has been less studied in a collective intelligence context [27,28]. Yet, timing decisions are just as consequential to the fitness of an animal [29,30]. For example, migration is ubiquitous among animals across many clades, and deciding when to migrate can have major fitness consequences by affecting the fat stores of the animal, weather conditions encountered along the way, and the breeding sites and mates available at the destination [31–35]. On shorter timescales, animals decide when to move locations throughout the day [36,37], which can affect the energy intake rate of an individual [38]. Moreover, animals must decide when to flee from an encroaching potential predator (often quantified in the literature as a ‘flight initiation distance’ [39] rather than a time) or, more generally, when to react to environmental cues [40,41], which can starkly determine whether the individual lives or dies [42].

Such timing decisions are often made by social animals living in groups. Synchronizing timing decisions across group members is essential to maintaining group cohesion, which is crucial to accruing the benefits of sociality [43,44]. As with spatial decisions, animals experience uncertainty about the optimal time to perform an action. Therefore, collective timing decisions could, in addition to simply maintaining cohesion, improve the precision and accuracy of the timing of actions by pooling the noisy estimates of multiple group members, or through other mechanisms (analogous to those described above for spatial decision making). However, heterogeneity within the group could also result in intrinsically different optimal leaving times across group members, which can cause conflict and ‘consensus costs’ [45,46].

Timing decisions have been studied extensively, but not in a collective context. This includes the timing of laying or hatching of eggs (e.g., [47]), migration [29], flight initiation distance [48], and intertemporal decision making (related to time discounting) [49]. Accordingly, theory has been developed to predict optimal leaving times through the marginal value theorem [50], optimal stopping theory [51], and in changing environmental conditions [52]. Among social species, research has demonstrated that social influence can affect timing decisions in a variety of taxa [28], including birds [53], mammals [54], and fish [55]. Some theory has been developed to examine how consensus costs can lead to different decision mechanisms evolving in timing decisions [45,46]. Synchronization (e.g., fireflies flashing [56] or ant activity levels within a colony [57]) is another well-known class of collective behavior. However, this is a coordination game because the fitness benefit arises from synchrony itself (i.e., consensus), rather than selecting an objectively optimal time. Therefore, we do not focus on synchrony here but note that it could involve similar or complementary social mechanisms. Overall, to our knowledge, there has been no work explicitly examining collective intelligence in timing decisions.

This near-exclusive focus on spatial, but not temporal, decisions leaves us with an incomplete understanding of collective intelligence in animal groups. Here, we argue that the mechanisms and dynamics underlying collective temporal decision making are likely to differ substantially compared with spatial decision making. Therefore, developing new theory and experiments specifically about collective temporal decisions is a fertile domain that will yield new insights into the function, adaptiveness, and evolution of collective intelligence in animals and could lead to valuable bio-inspired algorithms for engineered systems [58].

### Key differences between temporal and spatial collective decisions

Deciding among locations in space versus among moments in time differs in several key ways, which will almost certainly render our intuition gained from studies of the former inaccurate in making predictions about the latter. Here, we detail some of these crucial differences but anticipate that others will likely be revealed with more research.

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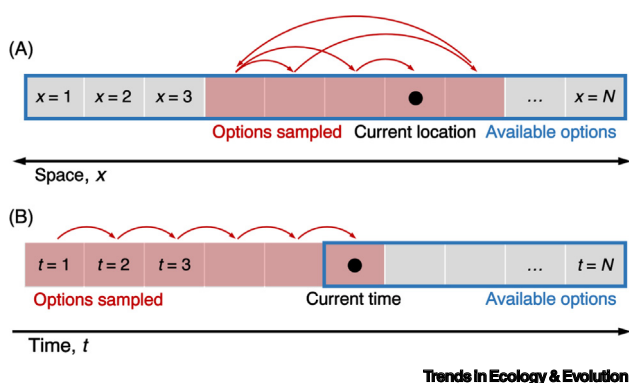
### Sequential ordering of time

In spatial decision making, multiple options are often available simultaneously and can be sampled in any order (Figure 1A). This can include discrete food patches [25], distinct routes [59], or continuous directions of movement [60]. An animal can then choose a direction or location that it has previously sampled, or one that has not yet been sampled. Such processes have been modeled using methods including multi-armed bandit problems [61], drift–diffusion models [62], and hidden Markov models [63].

By contrast, time can only proceed in a single direction. Temporal options are strictly ordered, and only one option is available at any time (i.e., the present moment). When a moment passes, it is no longer available as an option. Therefore, a choice asymmetry exists, with all past moments inaccessible to an animal and only future moments (or the present) potentially accessible (Figure 1B). Additionally, there is an informational asymmetry: animals can sample moments only in the past but cannot directly sample the future [64].

As an example, many animals must choose when to begin their seasonal migration. This process can be mapped into a series of yes–no (i.e., binary) decisions, whereby they decide whether to begin their migration at each passing moment [28]. To aid their decision, they could reference the weather conditions in previous days, their current physiological condition, and the decisions made by others to extrapolate into the future and predict when the optimal migration time might be. However, they are not able to replay the tape of the decision process and, therefore, can never know how close their chosen migration time was to the optimal one.

It may be possible for animals in groups to harness collective intelligence to make more accurate timing decisions, but constraints exist. Animals often signal when they want to depart, but do not have an explicit signal that they do not want to depart, leading to an asymmetry in the communication of preferences. A signal likely communicates that the animal is ready to leave now rather than communicating a desire to leave at a particular time in the future, further constraining the information that can be shared among group members. Finally, many signals are likely to be binary in nature, indicating a readiness to leave (or not leave), rather than a continuous measure of urgency or confidence ([45] but see [65]).



**Figure 1. Key differences between spatial and temporal decisions.** (A) For spatial decisions, many options can be sampled in a variety of orders and, in principle, all options remain available to the individual or group. (B) For temporal decisions, options are sampled strictly in order and, once in the past, sampled options are no longer available. A hallmark, and challenge, of temporal decisions is the lack of overlap between sampled and available options. By contrast, for spatial

decisions, there is a large (potentially complete) overlap in sampled and available options. (A,B) Both panels depict a discrete space/time option set (with arbitrary length/time units), but the same principles apply for continuous space/time.

This can lead to a conundrum in choosing when to begin signaling to go. If an individual begins signaling only when its perceived optimal leaving time has been reached, the group will almost certainly leave sometime after the preferred time of that individual. The optimal time to begin signaling depends on the cost of leaving at a suboptimal time, as well as the signaling strategies of other group members (i.e., game theory). However, if all of the individuals in the group signal to leave early, then this could bias the collective leaving time to be earlier than is optimal. These fundamental differences between spatial and temporal decision making necessitate new classes of decision models that can facilitate collective intelligence specifically in the time domain.

#### Asymmetric costs of too-early and too-late errors

Empirically, there is often an asymmetry between the cost of performing an action too early and performing it too late ([45] and stated in a more general context in [66]). For example, when an animal is foraging and is approached by a potential predator, the animal must decide when to flee. Leave too early and it misses out on foraging opportunities (a relatively minor cost), but attempt too late and it will be eaten (a very high cost) [48]. Similarly, animals that forage in tidally flooded river estuaries, such as bottlenose dolphins (*Tursiops aduncus*), suffer an opportunity cost if they return to the sea too early (relative to the onset of low tide) but risk being stranded and dying if they leave too late [67]. For seasonally migrating animals, arriving late to their breeding grounds could mean settling for a worse nest site and missing out on mating opportunities, but arriving too early could mean deadly weather conditions [68].

This asymmetry of costs is not built into most 'wisdom of crowds' models, where individuals in groups decide among a continuous set of values (e.g., what direction to travel or numerosity estimation) [43]. In many of these models, individuals adopt the average opinion as the collective decision, which usually results in improved decision accuracy [69,70]. Important exceptions exist for scenarios with discrete numbers of options, for example by using quorum rules to weight the collective decision toward one option [71,72].

By contrast, a simple average of estimates will not maximize fitness when an asymmetry of costs exists. Instead, animals should learn to estimate a time on the shallower side of the fitness curve (earlier in time in the example in Box 1). However, the wisdom of crowds could allow a larger group to estimate time more precisely, such that it can afford to perch closer to the objective optimal time, while smaller groups should choose a time further away from the optimal. If a social species exhibits fission–fusion dynamics (i.e., processes where groups are not stable; instead, the size and composition of groups can change often), these group size-specific optimal times can become problematic if an animal cannot accurately estimate the size of its group [6]. In particular, learning the group size-specific optimal time in a large group and then moving to a small group is likely to have larger fitness costs compared with the converse. In these situations, animals might simply learn the optimal time for a small group, thereby foregoing the potential benefits of the wisdom of crowds. Similar results would hold even if groups make decisions by utilizing a sub- or supermajority threshold rather than a simple majority rule.

#### Speed–accuracy tradeoff is non-monotonic

In decision theory, the 'speed–accuracy tradeoff' is a fundamental principle, where decision accuracy can be improved if the individual (or group) takes more time to accumulate more information, or faster decisions can be made but at the cost of lower accuracy [73,74]. However, the

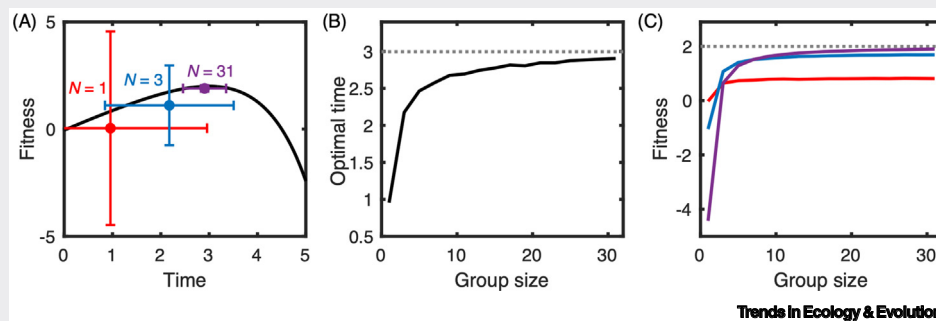
**Box 1. Asymmetric time costs can result in different optimal leaving times for different group sizes**

We illustrate through a simple mathematical model how the asymmetry of costs often observed in timing decisions confounds the predictions made by typical wisdom of crowds models (which are based on spatial decision making). Consider an animal foraging in a tidally flooded estuary. The individual consumes food linearly with the amount of time spent in the estuary, but the risk of being stranded (and, therefore, dying) increases exponentially the longer it remains. The overall fitness  $f$ , as a function of time  $t$  spent in the estuary, is described by  $f = t - \exp(t)/b$  for this example, with  $b = 20$ . The optimal time  $t^*$  spent foraging that maximizes fitness is  $t^* = \log(b) \sim 3.00$  (Figure 1A, black curve).

However, the above calculation assumes that animals can measure time perfectly, which they generally cannot. Therefore, we assume that an individual makes a noisy estimate of its desired leaving time  $t_D$ , which is normally distributed with mean  $t_D$  and standard deviation  $\sigma = 2$ .

We next consider groups ranging in size from  $N = 1$  to 31. Each individual estimates its desired leaving time  $t_D$  and signals to leave at that time. When half of the group has signaled, the group leaves. We scanned across  $t_D$  from  $-1$  to 3 and simulated the decision-making process 100 000 times for each set of parameter values  $N$  and  $t_D$ . We then calculated the value of  $t_D$  that maximized the mean fitness for that group size. Note that rather than choosing a desired leaving time and making a decision through simple majority rule, individuals could instead fix their desired leaving time and instead choose a sub- or supermajority threshold [71,72]; the conclusions remain the same.

Larger groups can choose a desired leaving time very close to the objective optimal time because the wisdom of crowds allows those groups to accurately identify that time (Figure 1A, purple), whereas smaller groups should opt to leave earlier to avoid the possibility of leaving late (Figure 1A, red and blue, and B). While individuals in large groups have the highest fitness, there is also a pitfall if group sizes frequently change (e.g., in fission–fusion populations). Given that animals in large groups are perched precariously near the objective optimal time, there is a severe cost in fitness if they then move to a very small group (Figure 1C). By contrast, animals in small groups, when moved into a large group, suffer less of a fitness cost. Therefore, in such populations, there may be a selection pressure to leave early regardless of group size, negating the benefits of the wisdom of crowds.



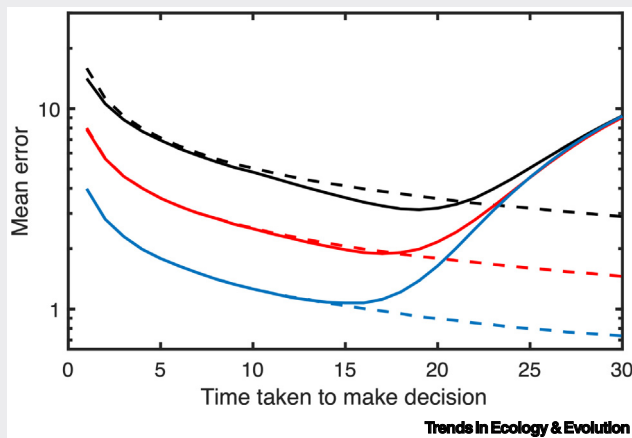
**Figure 1. Simple model of the consequences of asymmetric time costs.** (A) Fitness is asymmetric in time, where leaving early is less costly compared to leaving late (black curve). Smaller group sizes should leave early, but large groups can afford to be poised near the objective optimal leaving time. Error bars show 1 standard deviation in both dimensions. (B) The optimal leaving time scales nonlinearly with group size (black curve). Broken line shows the objective optimal leaving time [i.e., the peak of the black curve in (A)]. (C) The fitness when using the optimal leaving time for a particular group size [line colors, which match the colors in (A)] but transplanted to a different group size (x-axis). Using the optimal leaving time of a large group can have severe fitness costs when in a very small group (purple curve), but using the optimal leaving time of a small group has less severe costs (red and blue curves).

speed–accuracy tradeoff fails in the context of timing decisions. This is because spending more time gathering information simultaneously decreases the set of temporal options available to an animal (Figure 1B). Specifically, waiting longer could allow an animal to better estimate the optimal time, but also make it more likely that the optimal time lies in the past (and is no longer accessible). Therefore, waiting longer could improve decisions on short timescales but will lead to poor decisions on long timescales, resulting in an optimal decision speed (Box 2). What decision strategies are useful in these scenarios, and moreover, how collective intelligence interacts with these dynamics, are not known.

**Box 2. An optimal decision speed emerges in temporal decision making, replacing the classic speed–accuracy trade-off**

Here, we develop a simple model to demonstrate how the speed–accuracy tradeoff is fundamentally altered in the time domain. For each trial, we select an optimal value (location or time),  $\theta_n$ , by drawing a value from a normal distribution with mean  $\mu_\theta$  with standard deviation  $\sigma_\theta$  and rounding it to the nearest integer. During each trial, at each timestep (arbitrary time units), each individual makes a new independent estimate of the optimal value by drawing from a normal distribution with mean  $\theta_n$  and standard deviation  $\sigma_n$  (constant across trials). Individuals update their estimate by computing the mean of all of their estimates up to that point. The collective estimate is then updated by taking the mean of the estimates of all group members. For both spatial and temporal estimates, after a set number of time steps (i.e., the time taken to make decision), each group selects an option by rounding their current collective estimate to the nearest integer. However, for temporal estimates, if the desired time is before the current time (i.e., is in the past), their selection is updated to the current time. We calculate the error as the absolute value of the difference between the selected option and the optimal value,  $\theta_n$ . Finally, we average over trials to calculate the mean error as a function of time taken to make the decision (Figure 1).

For spatial decisions, where any option is available at any time, the error decreases approximately exponentially with increasing time taken (broken curves). This pattern reflects the classic speed–accuracy tradeoff. By contrast, for temporal decisions, in which options are lost as time passes, the speed–accuracy relationship is non-monotonic (unbroken lines). For short decision times, the temporal error decreases similarly to the spatial error. For intermediate decision times, the temporal error is (slightly) lower than the spatial error because, in the temporal context, the groups are insulated from large errors by selecting times that are far too early (in the past). This effect is reduced for larger groups because outlier guesses are rarer. For longer decision times, the error in temporal estimates increases dramatically (linearly) because, despite the group having an accurate estimate of the optimal time, the optimal time is almost always in the past.



**Figure 1. Speed–accuracy tradeoff in temporal versus spatial decisions.** For spatial decisions (broken lines), error drops monotonically with increased decision time. For temporal decisions (unbroken lines), error is minimized at a finite value of decision time and increases with additional decision time after this point. Colors correspond to different group sizes:  $N = 1$  (black/top),  $N = 4$  (red/middle), and  $N = 16$  (blue/bottom).

**Density-dependent strategies**

Game-theoretic considerations are often at play in timing decisions, due to the inherently directional nature of time. For example, there can be ‘finder’s fees’, whereby early deciders accrue more benefit by gaining access to more of a resource. Alternatively, the fitness of an individual could be affected by both its absolute timing and timing relative to conspecifics [75]. In other words, leaving when other groupmates leave could be just as important as leaving at a particular time, to maintain the benefits of group living [44]. How animals in a group negotiate different opinions among themselves to reach a consensus decision about a timing event is poorly understood (but see [43,76]).

These four examples illustrate that timing decisions and spatial decisions fundamentally differ in crucial aspects, especially in a collective context. If we simply apply our intuition

gained from the many studies of collective spatial decision making, we are likely to make incorrect predictions about animals making timing decisions. Therefore, new theoretical models are needed to describe animal groups deciding about when to perform an action. In particular, collective intelligence can arise during spatial decisions via several different known mechanisms, but it is not obvious which of these mechanisms may also apply to timing decisions, or if other, as-yet-undescribed mechanisms operate during timing decisions.

Of course, decisions are nearly always both spatial and temporal in nature. For some contexts, the decision may be decomposable into separate spatial and temporal components, with potentially different mechanisms used to make each subdecision (such as deciding when to start a migration, and then deciding the migration route). For other contexts, these will be inextricably tied. For example, in quorum sensing [77] or drift–diffusion models [62], the same mechanism determines both where to go and when. Increased focus is needed to determine to what extent these mechanisms can (or cannot) optimize both spatial and temporal components of a decision.

### Collective timing in the Anthropocene

A rigorous understanding of collective timing decisions is especially important now given ongoing shifts in our planet's climate. These changes could alter both the optimal time to perform an action and the timing of environmental cues to which many species have evolved to respond [78,79]. Understanding how collective intelligence can arise in timing decisions will shed light on the robustness of the associated mechanisms to perturbations, such as gradual or sudden shifts in the timing of cues [80,81]. In addition to shifts in the mean time of events, climate change is also expected to increase variability in timing [81], which could alter the optimal amount of time a group should invest in collecting information for a timing decision (Box 2).

With more uncertainty in the optimal timing of events, collective intelligence could become increasingly important for social animals to reduce noise and make sufficiently accurate timing decisions to survive in the Anthropocene. However, without a theoretical understanding of the mechanisms at play in collective timing decisions, we do not know whether collective behavior might help, or harm, the fitness of social animals in the face of shifts in climate.

In parallel to the collective response of nonhuman animals to climate change are the policy decisions that humans will make, or fail to make, to stem the tide of climate change [82,83]. Humans also face an asymmetry of costs here, where making policy changes too early could result in unnecessary economic costs, but making changes too late could lead to the global climate crossing effectively irreversible tipping points [84]. Given uncertainties in our climate models, it is probable that decisions should be made earlier than the objective optimal time.

### Concluding remarks

Collective behavior is ubiquitous across all scales of biological organization, from cells to social groups, and can lead to a variety of benefits to those organisms, including improved decision making. Understanding what mechanisms can give rise to collective intelligence can help to explain the evolutionary drivers of social species as well as their broader effects on ecological scales [85]. While collective decision making among spatial options is increasingly well understood, there is little, if any, work on collective decisions among temporal options. Simple thought experiments

### Outstanding questions

In what situations do known simple 'convergent' mechanisms (such as averaging) or emergent mechanisms (such as collective sensing or collective learning) lead to better timing decisions, and when do they fail?

What new collective decision-making mechanisms result in better timing decisions (but not spatial decisions)?

How do social processes for spatial and temporal decisions interact during decisions that involve both dimensions?

How does accuracy scale with group size when making timing decisions? Is the scaling similar or different to what is known for spatial decisions?

How does the optimal temporal strategy depend on group size? Can organisms measure the size of their own group, and do they need to?

The four differences between spatial and temporal decisions that we highlighted in this article are likely not exhaustive. What other fundamental differences exist?

Do constraints on the signaling by animals about temporal intentions (e.g., not being able to signal that they want to leave at some arbitrary time in the future) fundamentally limit the extent to which they can benefit from collective temporal intelligence?

How does heterogeneity in preference or position in the dominance hierarchy affect the collective temporal decision?

Are temporal decision-making strategies able to track shifting or increasingly noisy timing schedules? Do groups have a greater or reduced ability to adapt to a changing environment compared with individuals?

What are the population-level or ecological implications of organisms making collective temporal decisions (e.g., Allee effects)?

reveal fundamental differences between space and time that are likely to render many of the well-known ‘wisdom of crowds’ mechanisms to be ineffective when making timing decisions. Focusing specifically on the time domain should provide fertile ground for new and influential contributions to the field of collective intelligence, thereby expanding our understanding of social animals and humans alike (see [Outstanding questions](#)).

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### Declaration of interests

None declared by authors.

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