Agent, Behaviour, Trace, Repeat: Understanding the Cognitive Processes Involved in Human Stigmergic Coordination.

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Abstract

Stigmergy refers to the coordination of agents via artifacts of behaviours (behavioural traces) in the shared environment. Whilst primarily studied in biology and computer science/robotics, stigmergy underlies many human indirect interactions, both offline (e.g., trail building) and online (e.g., development of open-source software). In this review, we provide an introduction to stigmergy and emphasise how and where human stigmergy is distinct from animal or robot stigmergy, such as intentional communication via traces and causal inferences from the traces to the causing behaviour. Cognitive processes discussed on the agent level include attention, motivation, meaning and meta-cognition, as well as emergence/immergence, iterative learning and exploration/exploitation at the interface of individual agent and multi-agent systems. Characteristics of one-agent, two-agent and multi-agent systems are discussed and areas for future research highlighted.

Keywords: stigmergy; behavioural traces; indirect communication; cognition; complex social systems; multi-agent systems

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In the absence of synchronous communication or direct observation, the physical world helps us coordinate our actions with those of other agents in a common environment. Obvious examples are intentional messages delivered indirectly via the environment: "post-it" notes, printed signs and other labels. But there are more subtle forms: behavioural traces as unintentional by-products of actions taken also carry information that can be used by others. This includes information about social norms (all standby lights of unused PCs being off are traces of what is commonly done), categorisation (items placed in certain containers inform about correct placement), next steps to be taken (a nurse leaving instruments on the table that signal which examinations have yet to be carried out), temporary ownership (a coat placed on a chair), or successful courses of action (paths emerging from frequent use). Agents who make use of these traces will subsequently add their own traces in turn. An agent exploring a path, for instance, will reinforce it doing so. This feedback loop of environment-mediated, indirect coordination between agents using behavioural traces is called stigmergy. First coined by Grassé in 1959 (Bonabeau, 1999), the term is a composite of the Greek *stigma*, meaning "mark" or "sign", and *ergon*, for "work" or "action". Stigmergy originally meant to explain the paradox of how termites coordinate complex tasks such as building a nest despite the lack of direct communication between individual animals. In its most basic form, stigmergic coordination requires an *agent* performing an *action*, and a *medium* that "stores" or "remembers" the result of the action (i.e., the *behavioural trace*; Heylighen, 2016a).

Although often unrecognised, stigmergic coordination is ubiquitous in human interactions and can me more efficient than other, more prominent forms of coordination such as verbal communication or direct observation (Parunak, 2005). First, stigmergy allows for successful coordination between cognitively limited agents. Each agent requires only a limited set of simple rules to collectively produce results that they could not achieve on their own, such as termites' cathedral mounds several metres high (Theraulaz & Bonabeau, 1999). Since agents interact primarily locally, their processing capabilities are not overwhelmed by information from all other agents (Parunak, 2005). In theory this also applies to agents who are temporarily limited in their cognitive capacity, for instance because of distraction or competing task requirements — although this remains to be tested. Second, because traces can remain in the shared environment after the agent finished the behaviour, and sometimes long before another agent reacts to it, coordination can be asynchronous. Consequently, a trace can be observed by many other agents, usually a much larger number than could potentially observe the behaviour itself. This is especially the case for actions that tend to be private and/or fleeting. For example, recycling is usually done in the privacy of one's home; however, evidence of that behaviour, such as bins set-out on collection days, is observable in public. Third, no central controlling mechanism is necessary for coordination to be successful. Because stigmergic coordination does not rely on a specific order in which information is transmitted from one agent to the next, stigmergic coordination can be very resilient to adversarial agents obstructing parts of the system or hindering certain agents (Heylighen, 2016a). Fourth, free riders are less of an issue in stigmergic environments: Because behavioural traces usually persist after their informational value has been used by a single agent, they can be used by many others without them making further contributions. This can be observed in open-source software development (Besten, Dalle, & Galia, 2008; Bolici, Howison, & Crowston, 2016) and the creation of Wikipedia (Loveland & Reagle, 2013), where users who never contribute do not disrupt the system.

Stigmergy can be an efficient way to coordinate or distribute information about advantageous behaviours. Indeed, people use behavioural traces to inform their own behaviours in various contexts, such as path creation (Helbing et al., 1997a, 1997b), installation of solar panels (Baranzini, Carattini, & Péclat, 2017; Bollinger & Gillingham, 2012; Carattini, Levin, & Tavoni, 2019), donations (Jacob, Guéguen, & Boulbry, 2018; Kubo, Shoji, Tsuge, & Kuriyama, 2018; Martin & Randal, 2008; Reingen, 1982), littering (Cialdini, Reno, & Kallgren, 1990), and whether to switch lights off or on (Bergquist & Nilsson, 2016; Dwyer, Maki, & Rothman, 2015; Oceja & Berenguer, 2009). However, the cognitive mechanisms of human stigmergy have received relatively little attention. Stigmergy has been mainly addressed in the context of biology and robotics, and the ideas may be difficult to apply to human cognition, due to different terminology and theoretical frameworks. The aims of this paper are therefore to (a) introduce the basic elements of stigmergy, i.e., agents, actions, medium and traces, to an audience primarily interested in human cognition, and to illustrate them with examples from human experience; (b) delineate human stigmergy with regards to other forms of direct and indirect coordination; and finally (c) provide an overview of the cognitive processes involved on the agent and system levels, respectively.

The Basic Relationships of Medium, Agent and Trace

Agents create traces through their behaviours; in turn traces trigger new behaviours by the same or a different agent in a stochastic feedback loop (see *Figure 1* adapted from Heylighen, 2016a). The shared environment provides the medium which moderates whether a behavioural trace is possible at all and defines the range of potential characteristics of the trace. For instance, while repeatedly walking the same route on grass will naturally create a path, the same behaviour may not leave a trace on asphalt.

Medium and Agent

The medium needs to be accessible to the agents involved, and both *controllable* and *perceivable* (Heylighen, 2016a). The more affordances, that is opportunities for change or influence, the elements of a medium provide the more controllable it is (Dawson, 2014). For instance, most people would not be able to change the layout of an asphalt road, but

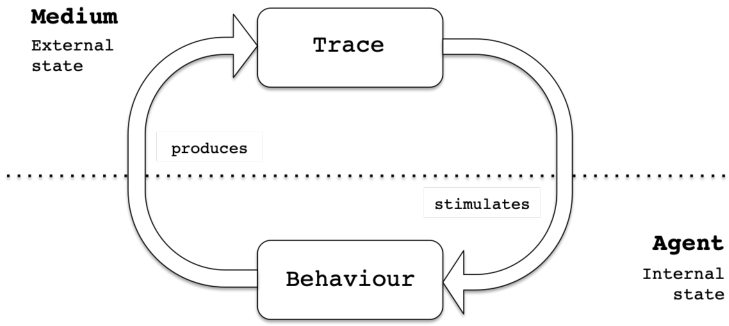

Figure 1. The basic stigmergic behaviour-trace loop, adapted from Heylighen (2016a)

could draw chalk directions on it. How perceivable a medium is will depend on a number of factors (Dipple, Raymond, & Docherty, 2014): First, its *topography* influences whether the medium is exclusive to local agents or available to a wider audience. This could be literally the topography of the environment such as steep mountains making a valley less accessible to outsiders, or the virtual topography of documents hidden behind paywalls or passwords. Second, in a more complex medium the sheer number or higher variety of elements will make each single element harder to distinguish. In other words, the medium's level of *entropy* affects perceivability. It is much easier to detect a specific item in an otherwise empty warehouse, compared to a store full of various products stacked in no particular order. Finally, the strength and number of various forces characteristic of a medium also influence its perceivability. Summarised under the term *dynamics*, this includes processes such as signal diffusion or erosion. The more forces come into play and the more complex their interactions, the harder it is to distinguish relevant features. Where fast vegetation growth, rain and frost interact, a path is much harder to distinguish from other path-like formations that lead nowhere in particular.

Medium and Trace

Entropy and dynamics of a medium result in a signal-to-noise ratio that determines whether a specific trace will be perceived: A chaotic environment with frequent changes will make detection of a trace much harder for the agent, compared to an orderly, static, or otherwise predictable environment. One important characteristic of a behavioural trace is its temporal duration—another consequence of the medium's dynamics. This is referred to as its *decay rate*, and determined through mechanisms such as diffusion and erosion. For instance, grass will grow back on a path that has not been used for some time. The decay rate varies on a continuum from highly transient (e.g., a scent or a sound) to more persistent (e.g., a building; Heylighen, 2016b). Although every trace will deteriorate over time, an agent may perceive a trace as persistent if it exceeds her lifetime, such as the Egyptian pyramids. Decay rates can be deterministic where traces expire after a fixed time interval, for instance when the streets are cleaned of litter on a particular weekday. More likely, decay rates vary according to some distribution: some items of litter are picked up by conscientious people, others are removed by the wind, whilst some escape the city's street sweepers (Marshall et al., 2011). Behavioural traces have to persist long enough to allow for them to be detected (Mittal, 2013), but should deteriorate when no longer relevant so that they are not deceptive (Heylighen, 2016b). Research into optimal decay rates is sparse and the optimal rate is likely dependent on the specifics of the environment, the agents, and the behaviour. For instance, consider the example of path creation in a meadow. For simplicity, suppose there are two potential points on the other side of the meadow which are worthy of visit, which one varies over time. If the decay rate is low, then there will likely be two indistinguishable paths. If the decay rate is very high, there may be no path visible at all. In this case, the optimal rate of decay will depend on the volatility of the environment (how quickly the goal changes) and the rate at which new agents enter the meadow, who can follow a trace and refresh or strengthen it. An additional factor will be how well agents can perceive small differences in trace strength. An analysis of the optimal decay rate might proceed in an analogous manner to the the rational analysis of memory (Anderson & Milson, 1989).

Agent and Trace

As agents create traces, they trigger behaviours in other agents who subsequently create more traces themselves. For instance, more people using an emerging path will make this path more usable, thus more people will choose the same path over less developed paths in the future (Helbing et al., 1997a, 1997b). The action triggered by a trace can be the same that created the trace in the first place or a different action. The trace can make the action more likely (positive feedback) but also less likely (negative feedback). For instance, traces of a resource being overused, such as cars on a particular route, may lead agents to balance this by using a different route, a different mode of transport, or not travel at all at certain times. These feedback loops have also been described as *herding* and *dispersing behaviours*, respectively— adopting the same or opposite behaviour (Banerjee, 1992), but have not been looked at explicitly for behavioural traces.

The stigmergy literature additionally distinguishes between two types of traces. The first type is *quantitative*, where an increase in the number of traces makes the subsequent action more (positive feedback) or less likely (negative feedback). Quantitative traces are illustrated by more people using a path hence making it more passable; or more citations of an article making it more likely to be cited again. The second type of traces is *qualitative*. Depending on the source, this means that either different types of traces or their combinations stimulate different actions (Dipple et al., 2014; Huang, Ren, & Jin, 2008) or the same trace stimulates different actions depending on agent or context characteristics (Heylighen, 2016b; Marsh & Onof, 2008). Regardless of which of these definitions one might adhere to, it is not obvious how qualitative traces differ substantially from quantitative traces. Quantitative traces can also stimulate different behaviours depending on characteristics of the trace, agent and context. A path that has been walked frequently may make it more likely that a cautious agent walks it, but a more adventurous agent may prefer the less travelled alternative—does this make the path a quantitative or qualitative trace? Rather than categorizing traces as quantitative or qualitative, we suggest that it is more sensible —at least in the human context—to determine the form of the relation between the number of traces and subsequent behaviour. The effect of traces on behaviour is not necessarily linear. For some traces a threshold may need to be reached, after which each additional trace makes the behaviour more likely. For other traces a saturation point may mean that any additional trace after that has less, no, or the opposite effect (Dipple et al., 2014; Huang et al., 2008). In some contexts one trace (compared to none or many) has a special status, perhaps because it draws attention towards certain attributes of the environment. For instance, while more pieces of litter make it more likely that subsequent people litter themselves, a single piece of litter makes it less likely (even less so than with no litter)—possibly because this single item highlights the overall cleanliness of the environment (Cialdini et al., 1990).

Agents can also wilfully *remove* traces, which underlines the communicative aspect of traces—something we will take up again in the following sections. Figure 2 summarises important external (dependent on the characteristics of the medium) and internal processes (dependent on the characteristics of the agents) involved in the creation and perception of a trace.

Delineating Stigmergy

Without further restrictions, each and every interaction would qualify as stigmergic. Speech is mediated through the environment as soundwaves and would thus qualify as stigmergic. Yet a direct conversation allows the speaker to adapt his speech to the listener in real-time in a way that is qualitatively different from a letter or post-it note. For the concept of stigmergy to be meaningful it needs better defined boundaries. Here, we take the view that the behavioural traces involved in meaningful stigmergy should minimally (1) outlive their constituting behaviour and (2) not be influenced by direct observation of the receiving agent's reaction.

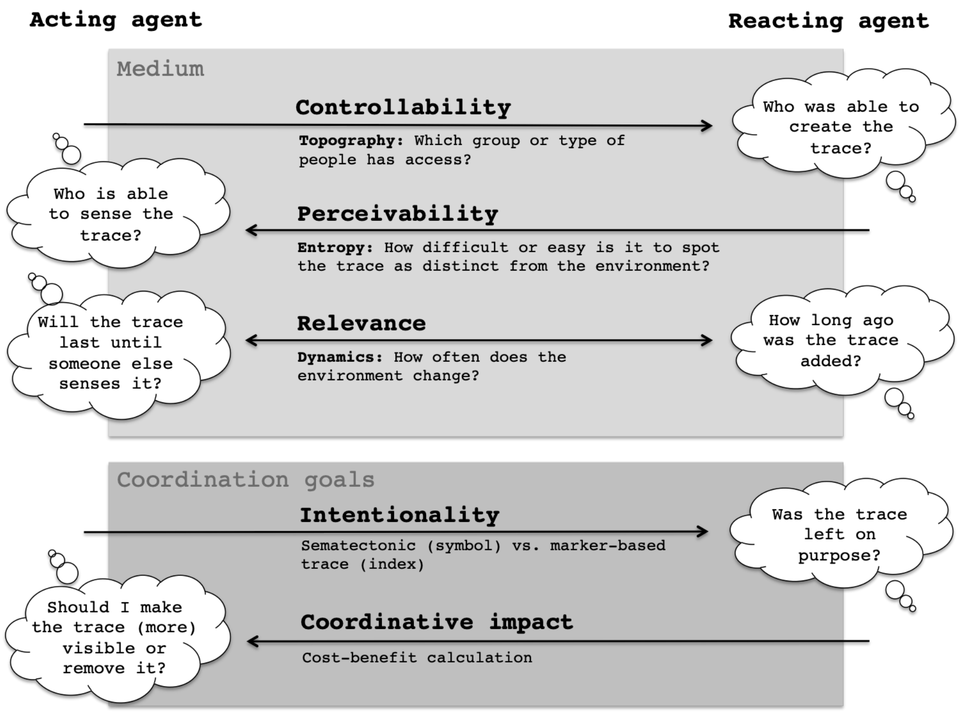

Figure 2. External and internal processes involved in the creation and perception of traces and the questions acting and reacting agents may ask of the trace (implicitly or explicitly).

Direct speech is a case where two grey areas of stigmergy align: *highly transient traces* and *conflation with direct observation*. With regards to the former, some have argued that a physical occurrence only counts as a trace if it can be later reviewed, such as a letter (Clark & Brennan, 1991). This, however, does not define how persistent a trace needs to be or for how long it needs to be reviewable. Minimally, the trace needs to remain available for longer than the behaviour that produces it, so that asynchronous coordination is at least in theory possible. Direct speech should therefore be excluded in this definition of stigmergy on account of it being too transient. Moreover, direct speech is also observed directly, and the trace itself may be influenced by the reaction of the observer. For example, the speaker may use different words or choose another topic altogether in response to a puzzled look or raised eyebrow. An online chat (whether written or via video conference application) is more obviously mediated by objects in the environment. Yet even though it may be reviewable later through a recording, it does not qualify as stigmergic either since—just as with offline, direct speech the next action by one agent is not independent of the receiver's presence. In contrast, comments on a shared electronic document qualify as stigmergic in this definition since they are independent of the agent's direct observation of the recipient's reaction. Of course, the creation of a trace may be influenced by the agent's *anticipation* of the recipient's reaction. This is fine, as this is entirely dependent on the producing agent's a priori beliefs about the receiving agent, and the receiving agent's actual behaviour plays no unique role in the creation of the trace. Some authors argue that something is stigmergic only if the behaviour does not have a predefined recipient (Consiglio, 2019). Yet this definition would exclude traces such as emails and post-its on a specific colleague's desk as well as self-stigmergy—unless one is willing to say that the recipient is not necessarily one's Thursday-self but could just as well be one's Friday- or weekend-self, a line of argument that would also apply to the colleague and thus reintroduce emails and post-its. We suggest that while traces directed at a specific person, self or other, is part of stigmergy, it is a special case that implies specific insight into the other agent's cognition and generalisations from this specific case to other areas of stigmergy should be made cautiously, if at all.

Nevertheless, direct observation can take place simultaneously to the creation of the trace, as long as it is not a constituent factor: People can be traces when queuing for a shop or event. This can in fact be a valuable source of information about the quality of a place or its services and products. Here the creation of the trace is not conflated with direct observation as long as the queuing is independent of being observed. In other words, if an agent wants to make a purchase and is thus queuing to be served, *and* her queuing is not substantially changed by whether other people can observe her, this action and its trace are stigmergic. If the same agent is queuing outside a club with the sole purpose of being seen (and thus would not queue if the agent did not expect to be observed), this is not stigmergic but a form of non-verbal direct communication.

In summary, we suggest that as the transience of traces is a continuum, *highly* *transient traces* should be considered stigmergic as long as they outlive the causing behaviour. For instance, the smell of a pizza may linger in a train carriage long after it has been eaten or the smell of fire can alert people long after it has been lit. In contrast, traces created in situations where *direct observation* is a constituent factor of the interaction should not be considered stigmergic for reasons outlined above.

Cognitive Mechanisms on the Agent Level

Which mechanisms enable stigmergic coordination on the agent level?[1]. For this, we will differentiate between mechanisms affecting agents who (a) create or remove a trace and (b) perceive the trace (see also *Figure 3*). One focus will be on the differences between the animal and robotics origins of stigmergy on the one hand and human stigmergy on the other hand, bearing in mind that there may be no traits unique to human cognition, only areas in which humans excel (e.g., tool use and social cognition) likely because higher interconnectivity between and flexibility of cognitive domains (Laland & Seed, 2021).

Acting Agent

Depending on the acting agent's goal with respect to coordination, behavioural traces can be differentiated as (a) *sematectonic*, where traces are unintentional by-products of the action and (b) *marker-based*, where traces are left intentionally as a signals to others (Dipple et al., 2014; Heylighen, 2016b; Wilson, 1975). These are sometimes also

[1] Although some authors have used stigmergic processes to explain, for example, brain activity through neurotransmitters (Correia, Sebastião, & Santana, 2017) and organs communicating via hormones (Heylighen, 2016a), for our purposes the agent will be the smallest unit. Note also that some authors have differentiated "classic" from "virtual" (i.e., web-based or online) and "cognitive" stigmergy (i.e., transmission and evolution of ideas). Since both "virtual" and "cognitive" stigmergy relate to physical entities (e.g., a server structure, cables and other signal transmitters; books and other documents), we do not see a need to emphasise this distinction.

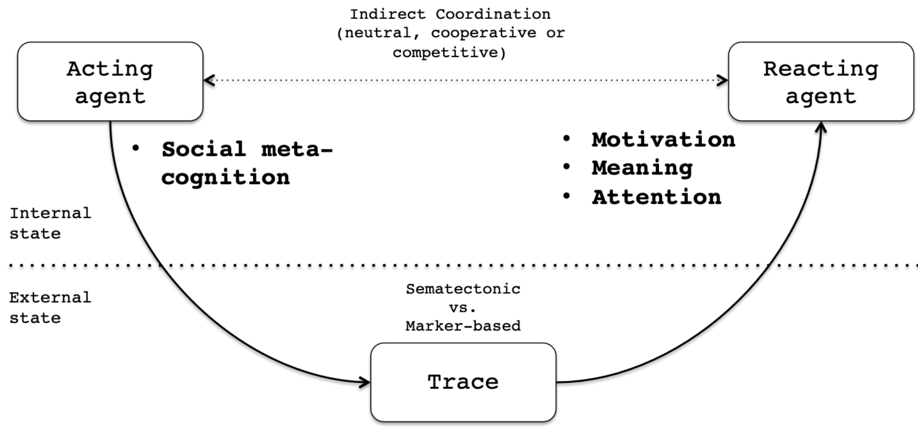

Figure 3. Key cognitive processes involved for acting and reacting agents.

respectively referred to as "index" and "symbol" traces (Consiglio, 2019). An example of a sematectonic trace is a path formed after repeated use, where the path is the by-product of someone traversing between two places. A marker-based trace would be the path created by someone specifically trampling the grass to mark where the agent wants others to follows. There are three distinct stigmergic scenarios to consider: Firstly, the behaviour automatically creates a trace at no extra cost and the trace can not, or at least not easily, be removed, such as in the path example. Secondly, the behaviour does not create a trace unless extra effort is invested, for instance keeping track of tasks in a separate spreadsheet. Thirdly, a trace is automatically created but the agent can remove it at an additional cost, such as committing a crime and then wiping all surfaces to remove finger prints. The fourth possible scenario that no trace is created and it is not possible to add a trace is obviously not stigmergic due to the lack of any traces. Scenario 1 is sematectonic since the trace is a by-product without any additional effort to add or remove a trace; scenarios 2 and 3 are marker-based and the acting agent will want to balance the costs of creating/removing the trace with the potential benefit of revealing/hiding her behaviour. Although this distinction between sematectonic and marker-based traces can be helpful, a behavioural trace can also be partly intended (Castelfranchi, 2009). When two behaviours provide the same outcome but produce different traces, the intention to *also* signal can be a deciding factor, for instance in consumer choices (Heffetz, 2011). A trace may thus be better thought of as a continuum from sematectonic to marker-based.

In order to influence other agents with marker-based traces, the agent will need to know that her behaviour produces a trace as well as have some understanding of her audience's knowledge of the meaning of that trace. In other words, the agent needs *social meta-cognition* (Chiu & Kuo, 2009) to know whether others can (a) access, (b) perceive, (c) understand and (d) agree with a trace or the underlying behaviour (Dillenbourg & Traum, 2006). Especially in competitive coordination the agent would not want to leak information to adversarial others. In this case they need higher-order social reasoning in the format of "I know that you know that I know…" to understand which traces mislead or give the opponent advantages (Verbrugge, 2009). This ability develops in childhood and, although prone to errors (Wimmer & Perner, 1983) is likely more sophisticated in humans than animals—most animals, for instance, do not reason beyond first-level meta-cognition (Carruthers, 2008)—, but potentially less in humans compared with AI/robots.

Reacting Agent

While animals can "read" traces to indirectly coordinate when they are of practical use or hard-wired (such as pheromones), yet humans are unique in their ability to generate and interpret abstract symbols, especially combinations of symbols (Laland & Seed, 2021). Marker-based traces, for instance, may be placed by the acting agent in a specific way to communicate additional information such as tools laid out from left to right to indicate tasks should be completed in a specific order. Combinations of marker-based traces may have a different meaning than each trace on its own. For instance a letter with some money by the front of the door meaning "please buy a stamp and post this letter", while a letter or money each on their own have many alternative meanings. Also, inferences that can be made from sematectonic traces (beyond the fact that these alterations to the environment in themselves may ease or complicate the task of a subsequent agent), can require a level of causal and social reasoning not likely found in other species.

In addition to the mere presence of traces, Dipple et al. (2014) argue that successful human stigmergy depends on the agent's *motivation* and her understanding of the *meaning* of traces.

Motivation. Motivation can refer to wanting to coordinate or wanting to engage in the behaviour. In contrast to Dipple et al. (2014), we argue that neither is necessary for stigmergy. First, there is no need for a specific motivation to coordinate. Consider an agent crossing a meadow who in the course of doing so tramples the grass to the ground. The agent does this frequently so that the grass is shorter where the agent has walked more. This will facilitate future crossings by her as well as other agents. Neither the first nor any following agents require motivation to coordinate. The motivation to cross the meadow is enough for the path to emerge. Nevertheless, a trace can offer information to the reacting agent at a cost lower than information gained from trial-and-error learning (Danchin, Giraldeau, Valone, & Wagner, 2004). For instance a well trodden path may be the best route established by many other walkers so the agent does not have to try all possible routes themselves. Hence, an agent may be motivated to attend to traces. Second, an agent does not need any prior motivation to engage in the behaviour that created the trace. On the contrary, seeing a well-used path may instil a desire to see what is on the other end—after all, if other agents went through the trouble of walking the route often enough to create a path, surely there must be something desirable at the other end (Marsh & Onof, 2008).

Meaning. Stigmergic coordination is aided by knowledge about the meaning of the trace (Dipple et al., 2014): Whether an agent is likely to follow a well-used path may depend on her understanding that the trace was created by an intentional behaviour and is not just a random occurrence. Apart from knowledge about a trace's *representation* (how the trace is supported by the environment and how it is transmitted to the agent's senses), *denotation* (how the trace was created) and *connotation* (previous experience with the context of a trace which enables causal inference) can help distinguish between helpful and misleading traces (Huang et al., 2008). Any additional knowledge such as whether a behavioural trace is likely marker-based or sematectonic and whether it was created by a specific group of agents will help an individual establish whether the behavioural trace is relevant and beneficial to her. This is different from animals and robots where the meaning of a trace is more likely to be hard-wired.

Establishing the meaning of a trace is not always straightforward: If a trace is the by-product of a behaviour (sematectonic) it is easier to decode, provided the most likely causing behaviour can be inferred. Marker-based traces depend more on context-specific knowledge such as whether it was left by a collaborator or competitor. In a cooperative scenario the trace was likely created to aid the reacting agent, for instance through tools left in places where they are next needed. In a competitive scenario the trace may have been created to confuse the reacting agent, akin to misleading evidence in a crime scene. Differentiating between sematectonic and marker-based traces is a non-trivial task that requires inference from objects to invisible causes, but one that humans are much better adapted to solve than most animals (Laland & Seed, 2021).

The inference from a trace to its probable cause is referred to as abductive reasoning (Consiglio, 2019). Unlike deductive reasoning where following logical steps leads to a single valid conclusion, abductive reasoning provides likely but uncertain explanations. Indeed, human agents tend to spontaneously generate possible purposes of unknown objects from an early age (Kelemen, 2000). A number of causal inferences can be made from traces, including (a) the *presence/absence* of an agent can be signalled by lights in a window visible from outside and may deter thieves; (b) *intention/commitment/goals* of an agent, for instance laying out certain tools may signal an agent is committed to repairing an item; (c) *ability/opportunity* such as a path up a steep mountain slope suggests that the ascent has been done before and is therefore possible; (d) *completion* as in the presence of a finished object signalling this work does not need to be done again; (e) *qualities of objects* *or relationships*, for example a machine in a waiting room dispensing paper slips with numbers inform a newcomer of the calling process, thus the newcomer obtains a number herself and waits (shortened from Tummolini & Castelfranchi, 2006).

Although understanding the meaning of a trace can help make use of it, this is not as essential as previously argued (e.g., Dipple et al., 2014). A path will be easier to walk than a field with tall grass, even though it may be unknown whether the cause is other walkers, animals, or geological peculiarities. Moreover, in human stigmergy cooperating agents tend to deliver the meaning of a trace through labels and legends (Susi, 2016), for instance as headers or extra columns in shared spreadsheets. Otherwise, the meaning of a trace has to be learnt just as any other cultural reference—through experience or direct communication.

Noticing a trace: Attention, Salience and Familiarity. A trace must be accessible to the agent's senses (*perceivable*; Heylighen, 2016a), but it must also be actually perceived. This includes being able to distinguish an object from its environment, something that is not trivial in itself (see further Fields & Levin, 2020). If motivation is given, attention will likely be directed top-down (*relevance* in Susi, 2016). Agent actively search for a trace they deem helpful (meaning of traces known) or explore the environment for anything that may be relevant (meaning of traces unknown). If motivation is missing, attention will likely be bottom up: A salient trace may create the motivation to use the trace (meaning known). Intuitively, there may be a reason why post-it notes are generally traded in signal colours. Especially when the meaning is not known, the trace must be salient enough to stand out, since unfamiliar (features of) objects tend to be overlooked unless explicitly pointed out (Modigliani, Loverock, & Kirson, 1998). This likely depends on features of the trace, e.g., its intensity with respect to size, colour, luminance, etc. (Itti & Koch, 2000; see *intrusiveness* in Susi, 2016) but also the number and frequency of similar traces as well as the trace's contrast with the environment (see also *entropy of the medium* above; Tatler, Baddeley, & Gilchrist, 2005). Indeed, larger and more visible solar panels are more likely to trigger more installations of solar panels in the neighbourhood (Baranzini et al., 2017; Bollinger & Gillingham, 2012; Carattini et al., 2019).

In addition, if an agent has memory of the environment's last state, any changes will be more salient. If the agent expects the environment to be in a certain state (which need not be the state the agent remembers), but it appears in an unexpected way, this will draw her attention to the changes (*prediction error*; Clark, 2013). Although some claim that agents must remember the state of the environment for stigmergic coordination to occur (Mittal, 2013), this is not the case. If agents put an item on their to-do list, follow it when they next see it and tick it as done, they do not need to know how many items were on the list previously. If anything, using the environment as external memory reduces the need for the agent to remember (see self-stigmergy below). The agent however does need some memory to make sense of the removal of a trace. Removal of a trace is potentially more relevant in adversarial or competitive stigmergy so as to not provide the other party with an information advantage (Nieto-Gomez, 2016).

Acting Agent = Reacting Agent (Self-Stigmergy)

A special case of human stigmergy is when the acting and reacting agent are one and the same person. As computationally limited entities (Simon, 1956), the environment affords opportunities "to offload the epistemic burden with a reciprocal and cybernetic relation between our conceptual creativity and the environment, to intimate, regulate and inform concepts and action" (Marsh & Onof, 2008, p. 142). These offloaded artefacts are sometimes called *exograms*, in analogy to *engrams*, the memory records in the nervous system (Consiglio, 2019). Externalising tasks, especially those taxing working memory, can increase efficiency (Heylighen & Vidal, 2008). For instance, multiplying 234×8 on paper means that only those numbers currently operated on need to be held in working memory (e.g., 8×4 in the first step). Not only that, but once the agent has noted down "32", the structure of the task will prompt her to do 8×3 next. Other every-day examples are to-do lists, calendars, and notes, but also objects placed in locations to trigger a necessary action, such as a letter placed under the house keys so it will be posted the next time the person leaves the house. The environment not only scaffolds cognition as in the examples above, it can also augment it (Clark, 1997). Interaction with objects in the environment can increase performance in insight problems above the use of pen and paper (Henok, Vallée-Tourangeau, & Vallée-Tourangeau, 2020; Vallée-Tourangeau, Steffensen, Vallée-Tourangeau, & Sirota, 2016). Niche-creation, namely adapting the environment to make it more suitable to the individual (rather than the individual adapting to the environment) is not unique to but especially pronounced in humans (Kirsh, 1996).

Key Characteristics of Stigmergy in Multi-Agent Systems

Group performance can outperform the sum of individual contributions ("assembly bonus effect"; Collins & Guetzkow, 1964). This also applies to environment-mediated interactions of agents in a stigmergic system (Parunak, 2006). In this section we focus on two key aspects of stigmergic multi-agent systems that can give them a performance advantage: scalability and self-organisation (*Figure 4*).

Scalability

Increasing the number of agents in a system will increase overall power to complete a task, as long as they do not get in each other's way (Heylighen, 2016b). Multi-agent stigmergy likely evolved from self-stigmergy, starting with genetically near-identical individuals such as termites who use the environment in comparable ways (Theraulaz & Bonabeau, 1999).

"Offloading" happens not just on individual level. The environment acts as a collective memory system that agents can access and update not unlike a personal calendar, just on a bigger scale (Correia et al., 2017; Doyle & Marsh, 2013; Marsh & Onof, 2008). However, more agents also require more coordination. In traditional theories about

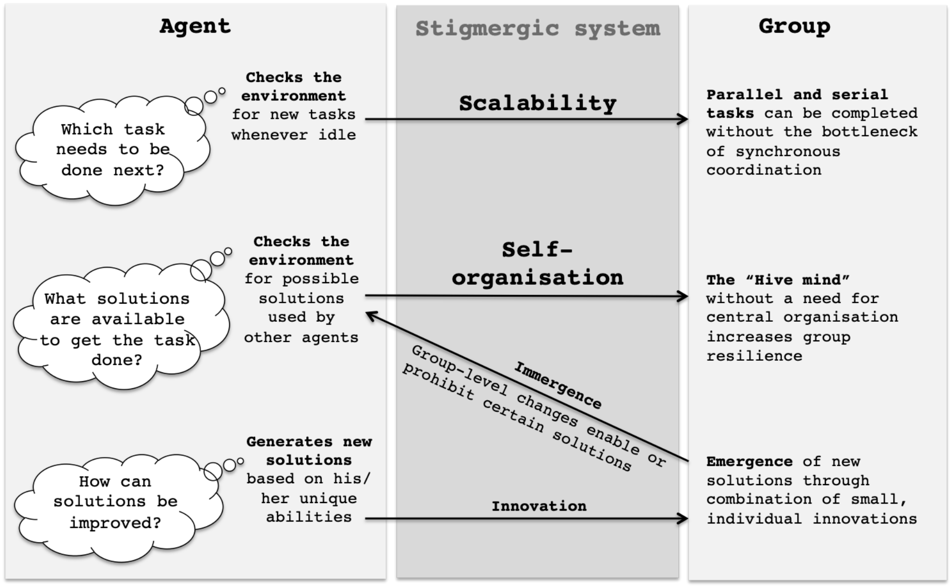

Figure 4. Key characteristis of a stigmergic multi-agent system and the dynamics on agent as well as group levels.

coordination of work, to make a system more efficient, one can either increase communication or decrease dependencies between agents (Bolici et al., 2016). Both are harder (or even impossible) to achieve the larger the system. Increasing communication requires at least some synchronicity—otherwise communication will slow down the process. Decreased dependencies make agents more autonomous but also reduce the power of several agents working on the same problem. Stigmergic coordination offers an alternative approach: It works for both actions that are prerequisite for later actions and actions that can run in parallel. In both cases the state of the environment will inform the agent of the necessary next step without having to increase communication or decrease dependencies.

This is not to say that stigmergic coordination is perfect. Bottlenecks exist if agents with special skills are required to complete a task (more on qualitative differences between agents in the next section). The system can also be inefficient if an agent has to repeatedly check the environment for traces before starting her next task (Heylighen, 2016a). Nevertheless, stigmergic multi-agent systems are generally more scalable than other forms of coordination. For instance, stigmergically coordinating human players outperform supercomputers in the search for new protein structures (see the game "Foldit"; Lewis & Bergin, 2016).

More agents can also create more confusion with regards to the meaning of a trace. There may be a credit assignment problem, when it is unclear whether one person created many traces, or many people each created few traces. In addition, the behaviour of many may precede creation of a more persistent trace (cycling lanes are introduced because many people cycle), but the trace may also precede the behaviour (an architect decides to pave parts of a development before any actual need arises). This latter issue changes the informational value of traces in two ways:

First, since the causal direction is less clear, it is harder for an agent to make inferences about the underlying behaviours—do many people cycle (because it is a superior type of transport) or would a policy-maker like people to cycle (but it is actually very dangerous)? In architecture, a path that forms next to paved alternatives (a "desire line"; Throgmorton & Eckstein, 2000) emerges for a reason—usually because the informal path is shorter. Where an easy option exists, yet traces show that an alternative is preferred, the persistent structures emphasise the contrasting preferences similar to a single piece of litter highlighting the overall clean context. Second, when a trace's life is artificially prolonged, it may lose its coordination value (Clark, 2013). An unused *trampled* path would normally disappear after a full growing season. But an unused *paved* path persists much longer. It hence no longer signals recent activity, and may even become deceptive if the places it connects have vanished or otherwise become unimportant (Heylighen, 2016b).

Self-Organisation, Emergence and Immergence

A stigmergic system can aid self-organised coordination of multiple agents (Lewis & Marsh, 2016). Since no central control mechanism is necessary, the stigmergic system is resilient to adversarial forces from outside the system (Lewis, 2013), meaning that agents can continue with their work despite single agents being hampered. In fact, frequent, local failures help establish more resilient global structures or procedures since only those will "survive" (i.e., agents are forced to learn and adapt). Where two systems compete, the one with fewer constraints, for instance due to fewer bureaucratic rules or flat hierarchies, will be more resilient (Nieto-Gomez, 2016). Stigmergically coordinating autonomous agents also solve tasks faster than centrally controlled agents, especially if the task is harder (Yong & Miikkulainen, 2009). In many examples of group-level creativity and innovation, agents are more likely to make incremental changes to the existing solutions rather than big leaps (Lewis & Bergin, 2016; Liverpool-Tasie & Winter-Nelson, 2012; Secretan, 2013; Wisdom & Goldstone, 2011), adding in turn to the resilience of the system as individual agents expose themselves less to exploitation by free-riders. Stigmergic coordination is also consistent with the phenomenon that small groups can have a disproportionate weight in the overall system (Montgomery & Casterline, 1996) if (a) the small group is either very dedicated and spreads behavioural traces more frequently, making a behaviour seem more prevalent than it actually is (Marsh & Onof, 2008), or (b) the minority's behavioural traces are so different that they attract more attention than those of the majority.

So far we have assumed that all agents are identical and only looked at the effect of increasing numbers in a system. However, more agents can add a qualitative improvement if they are diverse, i.e., they have different knowledge or skills (Heylighen, 2016b). For instance, groups of robots with heterogeneous strategies outperform homogeneous groups in a surveillance task (Tinoco & Oliveira, 2019). The diversity enables a system to produce novel patterns including new combinations of behaviours. This benefit of diversity, or "noise", does not just apply between, but also within agents: Surveillance robots are better at a task when their next step is chosen stochastically rather than deterministically (Tinoco & Oliveira, 2019). Since stigmergic coordination is not constrained by temporal and spatial synchronicity, it leads to more diverse learning opportunities than verbal communication or direct observation, hence increasing the chance of new, innovative behaviours to develop (Keil & Goldin, 2003). But stigmergy also ensures that not every new iteration becomes a rule: Only if several similar events happen to occur close in time or space are they likely to be picked up by other agents because enough traces are produced to attract attention or reach a decision threshold.

The occurrence of new (combinations of) behaviours is termed emergence. While *weak emergence* is reducible to rules on the agent level (e.g., Conways' *Game of Life*), *strong emergence* denotes a change in the overall system in a way that exceeds the sum of its constituents parts (Mittal, 2013). Emergence can thus only be observed on the system level. In a more stringent definition, strong emergence requires the changes on the system level to (a) be evolutionarily adaptive and (b) affect the individual (Bersini, 2012). In other words, the emergent behaviour fulfils some purpose that is independent from the observer. For instance, a flock of birds flying in a particular formation may be pretty to the human observer, but "beauty" is a weak and subjective criterion. Instead, the formations have emerged because they secure best survival chances against predators. Were it up to the observer to define new behaviours as emergent, it would depend on their ability to detect rules or patterns. Because emergent behaviours change how a system operates, it also forces individuals within the system to adapt. Without flock formations, an individual bird would only have to avoid colliding with other birds (which is not too different from not colliding with objects in general). Under the emergence of formations, the individual bird in addition needs to copy neighbours, while keeping a maximum and minimum distance (Bersini, 2012). The way agents are in turn affected by emergence is termed *immergence* (Kennedy, Eberhart, & Shi, 2001; Marsh & Onof, 2008). Although emergence and immergence are inseparable and occur simultaneously (Kennedy et al., 2001), their effects are distinct.

As an example from human stigmergy, social norms can be described in terms of emergence/immergence and help to illustrate their distinct effects. The social norm literature differentiates *descriptive* social norms ("is" norms) and *injunctive* social norms ("ought" norms; Cialdini et al., 1990). Instances of descriptive norms entail both third-party aggregate information ("70% of people do X") as well as individuals having direct access to evidence of that behaviour. However, the literature often subsumes direct and indirect observation (Lapinski & Rimal, 2005). Descriptive social norms are sometimes referred to as social proof (Goswami & Urminsky, 2016); other terms are social suggestion/ modelling/ learning/ information/ contagion. Of these, social contagion specifically refers to a small group of innovators spontaneously trying a new behaviour that a larger group of imitators later adopts (Bass, 1969). Simple social contagion requires only one exposure, while complex social contagion requires repeated contact with adopters (Centola, 2015). In contrast, injunctive norms emerge when they increase coordination efficiency (Voss, 2001) and may be enforced by both communication and/or incorporated in the shared environment. For example, if the majority of drivers adopt the behaviour "keep to the left" of the road, it benefits all other drivers to do the same (coordination efficiency). Traces of injunctive norms are predominately marker-based, here for instance signage and crash-barriers. The norm of driving on the left in turn impacts the individual agent by both making her journey safer. The norm is evolutionarily adaptive. But the norm is also limiting the agent. For instance, the agent may not be able to make a right turn where it would be convenient because crash barriers have been installed. The norm thus affects the individual. Norms can also lock a system into a suboptimal state: When new trail creation is costly, a system may settle for a path that is not necessarily the optimal solution. As it would be too costly for a single agent to divert from the existing path, the system limits the individual agent's behaviours to the system-wide solution (Gureckis & Goldstone, 2006).

Cognitive Mechanisms in Multi-Agent Systems

While the agent in self-stigmergy can have any set of preferred behaviours or beliefs and stick to those no matter what, these may (need to) be changed or updated by what the agent learns through others' traces. Depending on the context, various ways of learning are possible (for a review see Mesoudi, 2008). While associative learning from frequent observations of a behaviour and its resulting trace may help agents to understand the meaning of a trace, here we are concerned with learning on the system level that goes beyond the (most likely) meaning of a trace.

Iterated learning

A relatively simple form of knowledge transmission is iterated learning. Iterated learning occurs when, for instance, lights switched on or off in a room will be a trace for the next person entering the room, who will leave a trace for the person after that by switching the lights on or off, and so on. Iterated learning captures how "a behaviour arises in one individual through induction on the basis of observations of behaviour in another individual *who acquired that behaviour in the same way*." (Kirby, Griffiths, & Smith, 2014, p. 108, italics in original). It is a potential mechanism to formalise the evolution of behaviours within a system, except not through direct observation but via traces. Given some traces, learners infer the probability of hypotheses and, based on this, produce traces themselves. As an example, based on how many instances of an item someone sees in a recycling and trash bin, the agent makes an inference of the likelihood that the item is recyclable. The agent then disposes of her item, thereby generating a new trace. It is noteworthy that initial biases tend to become more pronounced with each transmission because each agent combines the available evidence of what agents have done before with their prior beliefs (Griffiths, Christian, & Kalish, 2008), so that if most agents have even a slight prior preference for one solution, this solution becomes increasingly more likely to be chosen with each additional agent.

Cultural learning in exploration / exploitation scenarios

Cultural learning occurs as imitation, instruction or collaborative learning (Tomasello, Kruger, Ratner, & Curran, 1993), depending on whether the teacher, learner or both are taking each other's perspective. Although often associated with synchronous learning including shared attention towards a specific object or situation, cultural learning can be environment-mediated. This minimally requires perspective-taking by either the acting or reacting agent, such as trying to understand whether a trace was placed intentionally. Information gathering on a group level, and how individuals benefit from this, is of particular interest in foraging and exploration/exploitation scenarios, which we will use to illustrate environment-mediated cultural learning.

The exploration-exploitation dilemma refers to the trade off between using a known resource (exploitation) versus spending time on finding an even better resource (exploration). On the group level, each individual has the additional option of learning from other people's exploration, for instance by knowing which areas have been explored (some footsteps) and which areas are highly desirable (many footsteps). Cultural learning combines two advantages for the group. First, it is cost-saving because acquiring information from others is usually less costly then exploring oneself. Second, the average accuracy of information increases over time as long as the information is trustworthy—and more so if individuals provide the information only if it reaches a threshold of certainty. Group level decisions in social insects are generally more accurate and less prone to violations of transitivity and independence of irrelevant alternatives (Sasaki & Pratt, 2018). This "wisdom of the crowd" effect has long been documented in humans (Galton, 1907), and has also been shown with indirect coordination via behavioural traces (here: "swarms"; Rosenberg, Baltaxe, & Pescetelli, 2016).

Traces inadvertently provided by agents engaged in efficient performance of their activities (sematectonic traces) can have different effects on the information provider: From *parasitism* (involving a cost to the acting agent, for instance because the reacting agent gains knowledge that provides them with an advantage; competitive stigmergy), *commensalism* (neutral effect for the acting agent), to *mutualism* (both acting and reacting agent benefit from the use of this information; cooperative stigmergy; Danchin et al., 2004). Despite the potential cost to some individuals, groups in which agents switch between individual and cultural learning outperform groups of individual learners in a dynamic environment (Kameda & Nakanishi, 2003; Mesoudi, 2008).

In turn, the question arises under what conditions people want to make their behaviour available or especially salient to others. Group-level decisions have been extensively modelled for social insects, for instance when finding new nesting sites. Here, the decision-making process includes exploration, communication, and quorum sensing (Marshall et al., 2011). In this process, ants who have found a high quality site recruit faster than ants who have found a low quality nest site (through so-called tandem-runs or pheromones). This creates a positive feedback loop for the high quality site as more individuals are recruited faster and recruit faster themselves in turn. Equally, humans who are more convinced of their strategy may (a) leave more traces, (b) more visible traces, or (c) remove opposed traces, thus creating positive feedback loops for the desired behaviour. In a series of three papers, Hunt and colleagues have shown how Bayesian models of nest selection, foraging, and externalised memory (Hunt et al., 2018a, 2018b; Baddeley, Franks, & Hunt, 2018) capture collective information processing in ants using both direct (tandem running) and indirect coordination (pheromone and carbohydrate traces). Although promising, their findings have yet to be tested on human subjects, both with and without the goal of cooperation/competition.

In diverse groups the number of explorers and exploiters will vary. Continued exploration keeps a stigmergically coordinating system adaptive despite long periods of stasis (Schoonderwoerd, Holland, Bruten, & Rothkrantz, 1997). That is, even though a best possible solution exists at that moment, this could become obstructed or obsolete later in time. Having alternative (albeit currently inefficient) routes readily available helps the group to adapt more quickly when changes occur. The level of exploration in a group may also influence the ideal decay rate of traces. In a simulation of garbage collecting robots, a robot that has collected waste will leave a trail of traces to signal where a lot of waste is currently being produced. Other robots can then follow this trail or explore less travelled areas and discover other locations with waste. Exploitation rates were set to different probabilities (all $> .5$)of following the trail with the highest number of traces. Out of three decay rates tested, the medium rate shows best performance in combination with the lowest exploitation (thus high exploration) rate (Alfeo et al., 2019). In other words, decay rate not only needs to correspond with the behaviour, but the characteristics of the agents and problem as well.

Summary

Stigmergy is a process of indirect coordination via behavioural traces in the shared environment. It can be a lens to better understand coordination of agents with themselves and within and across groups. Stigmergy was first described in social insects and has been predominantly researched in biology and robotics. In applying stigmergy to humans, we should lacks a framework that takes into account the difference between animal and human stigmergy. This paper focuses on human stigmergy and addresses differences between animal and human stigmergy by highlighting important cognitive mechanisms involved.

Traces can be described along a continuum of sematectonic (by-products) to marker-based (instructive) traces. Important cognitive mechanisms involved on the agent level are (a) *attention* to detect a trace, (b) *motivation* to use or ignore the information the trace holds, (c) various ways of *learning* the meaning of a trace, and (d) processes of *meta-cognition* when trying to communicate through traces. These mechanisms are not uniquely human; but they are arguably more complex in humans (Laland & Seed, 2021). On the group level, stigmergic coordination proves to be more *scalable* compared to alternatives such as increasing communication and decreasing inter-agent dependencies. Stigmergy enables *self-organisation* without a central controlling mechanism, and, when agents are diverse, *emergence* of new behaviours. Agents within these systems may learn adaptive behaviours (a) through *iterated learning* or (b) through *cultural learning* as illustrated in exploration/exploitation scenarios; agents may further (c) contribute through innovation and (d) are in turn affected by system-wide changes through *immergence*.

Future Research

Several relevant research questions follow from the above. First, since the majority of studies on human stigmergy concern collaboration in the workplace (Christensen, 2007, 2013; Cristancho & Field, 2020; Susi, 2016; Susi & Ziemke, 2001), the focus has been on marker-based traces in scenarios where there is motivation to coordinate with colleagues and the meaning of traces is agreed upon. Despite being common, sematectonic traces have received less attention. This introduces a number of important questions: Do people understand the meaning of traces, i.e., are they able to infer the behaviour from the trace? Knowing the meaning of a trace is not essential for its use (as in the example of a well walked path), yet we would expect opportunities for coordination to be enhanced if the meaning is understood. Why and how do people learn the meaning of a trace? How salient or frequent does a trace need to be before someone seeks to understand it (and searches for additional information, e.g., ask someone who may know; Heylighen & Vidal, 2008)? Related to this, when are salient and/or frequent traces ignored? A working hypothesis is that motivation to cooperate or compete will make it more likely that agents will actively engage to learn the meaning of a trace. Assuming a type of trace is there for a reason, the agent will likely pay more attention to contexts in which those traces occur (associative learning), or tap into additional sources of information (cultural learning). However, if agents have no motivation or navigate an environment randomly, they may still learn the meaning of traces through associative learning.

Second, to what extent do people consider others when creating a trace, especially when the trace is a by-product of their behaviour? When people can choose whether or not to leave (or remove) a trace, what influences this cost/benefit analysis? A working hypothesis is that when the behaviour is in line with norms or otherwise cooperative, they are more likely to reveal it in neutral or cooperative settings. People will be more likely to hide traces in a competitive setting, especially when the meaning of a trace is well understood. A related question is whether people who are more convinced of their strategy leave more or more visible traces, just like social insects recruit faster for a high quality nest site (Marshall et al., 2011) and in a similar way to how people signal characteristics of their self such as their wealth (Heffetz, 2011) or how pro-environmental they are (Brick, Sherman, & Kim, 2017; Griskevicius, Tybur, & Van den Bergh, 2010) through the products they buy and display.

Third, how well can people learn from traces in different settings? When traces of only of the previous person are accessible, we would expect that, as in iterated learning scenarios, initial biases will become more pronounced over time. On the other hand, in settings where traces of all relevant previous behaviours are available, the amount of information may be overwhelming, and people may rely more on their prior beliefs and less on available traces where all information is available.

Fourth, what trace decay rate is optimal for indirect coordination? This likely depends on the behaviour in question as well as the wider context, such as how often the behaviour is performed, how long it takes to create the trace, how visible the trace is, and how often other agents encounter the traces. Characteristics of the medium and agents likely also influence the ideal decay rate. If the physical environment or an agents' goals change quickly, traces should decay more quickly to stay relevant. In a population of exploiters where exploration would be advantageous, the optimal decay rate should be relatively higher (faster deterioration) compared with a population of explorers or where exploitation is the best strategy. In many situations, the optimal decay rate will likely follow an inverse u-shaped function, where very short and very long decay rates are less helpful for rates of coordination than intermediate decay rates (Clark, 2013; Heylighen, 2016b; Mittal, 2013; Storm & Patel, 2014; Williams, Hong, Kang, Carlisle, & Woodman, 2013).

Fifth, new behaviours emerge from the interaction of diverse individuals within a system. For instance, cooperation can emerge as a successful strategy in a social dilemma in the absence of repeated interactions or punishments, as players learn successful strategies through behavioural traces (Chiong & Kirley, 2012). The simple rule "follow what others have done right, regardless of who they are" (Chiong & Kirley, 2012, p. 14) circumvents direct ways of social learning that depend on knowing, trusting or liking the other person. However, usually these are examples of weak emergence because participants have a finite number of actions to choose from. In order to model strong emergence (and immergence) of a system, the parameters on the agent level would need to be free to vary, at the very least within a pre-determined range. Other ways to investigate emergence are designs were group members who engage in a common task are replaced over time and performance is compared with groups where no interchange of members has taken place. This method could be used to study the effect of diversity in the emergence of novel behaviours, spread of behaviours between groups within a system and self-selection to groups, based on behavioural traces.

Conclusions

Like animals and robots, humans are embedded in the physical environment and interact with it through our bodies and the tools we use. Many of our actions leave traces in the shared environment and can inform others of what has been, could, or should be done. In contrast to animals and robots, where many of the links between traces and behaviours are automatic or "hard-wired", traces in the human sphere have cultural-specific connotations and the cognitive processes at work are more complex, for instance second- and third level meta-cognition and theory of mind. Investigating how behavioural traces are first created and then interpreted, independent of other channels of communication such as direct observation and speech, contributes to our understanding of how people learn from and coordinate with each other. Future findings can be used to make coordination more efficient and less error prone. Behavioural traces also lend themselves to interventions: Traces of beneficial behaviour can be made more, and traces of undesirable behaviour less visible, either by changing their attributes, decay rates or the frequency with which they are produced. Although not well investigated as an intervention strategy, this could increase the prevalence of the desired behaviour with relatively cost-efficient design changes. This might be especially relevant in politically polarizing issues such as climate change.

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