Cell migration: from tissue culture to embryos

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ABSTRACT

Cell migration is a fundamental process that occurs during embryonic development. Classic studies using in vitro culture systems have been instrumental in dissecting the principles of cell motility and highlighting how cells make use of topographical features of the substrate, cell-cell contacts, and chemical and physical environmental signals to direct their locomotion. Here, we review the guidance principles of in vitro cell locomotion and examine how they control directed cell migration in vivo during development. We focus on developmental examples in which individual guidance mechanisms have been clearly dissected, and for which the interactions among guidance cues have been explored. We also discuss how the migratory behaviours elicited by guidance mechanisms generate the stereotypical patterns of migration that shape tissues in the developing embryo.

KEY WORDS: Cell migration, Guidance cues, Environmental signals, Cell-cell contact, Tissue culture, Embryo development

Introduction

In the early 1900s, the biologist Ross Harrison developed a method for growing embryonic cells outside the body. He had wanted to observe whether nerve cells were capable of extending axons during development but the opacity of amphibian embryos and the lack of suitable microscopic techniques precluded his examination. To overcome these restrictions, Harrison developed an in vitro assay in which he cultured explants of amphibian nerve tissue on a dish. Using light microscopy, he was then able to reveal that axons were the result of extensions of single nerve cells (Harrison et al., 1907). Since Harrison’s pioneering use of two-dimensional (2D) tissue culture systems, this technique has become fundamental in the study of cell locomotion in real time.

Over time, it became evident that cells in 2D culture, three-dimensional (3D) culture and in vivo contexts show pronounced differences in cell shape, cell-matrix adhesions and migratory behaviour. Nonetheless, studies of in vitro culture systems have served to define major guidance mechanisms of cell migration that rely on intrinsic cell motility, topographical features of the substrate, cell-cell contacts, and chemical and physical environmental cues. In vivo analyses using a variety of vertebrate and invertebrate model organisms that offer amenability for embryo and tissue handling, optical imaging and genetic manipulation have provided insights into how the in vitro guidance mechanisms operate in the context of embryonic development. Here, we review these mechanisms and examine how the migratory behaviours elicited in response to guidance cues work to generate the patterns of individual and collective cell migration that shape tissues in developing embryos. We begin by providing an overview of the types of cell migration that occur in cultured cells in vitro and discussing their underlying principles. We then discuss how these principles apply to the various examples of cell migration that occur in vivo during embryonic development.

Random cell migration in vitro

Much of our insight into cell migration has come from time-lapse studies of fibroblasts cultured in vitro. When plated on 2D surfaces, fibroblasts lose their round morphology and spread to increase their apparent surface area. A few minutes later, they develop multiple peripheral cell protrusions (lamellae) and, as adhesion increases, one lamella becomes dominant and fibroblasts develop a clear front-to-back polarity. This acquisition of cell polarity is fundamental to initiate locomotion and depends on the differential activity of small GTPases such as Cdc42, Rac and RhoA, which regulate actin dynamics, adhesion organisation and protrusion formation (Box 1).

Box 1. Front-to-back polarity in a migrating cell

A key morphological readout of front-to-back polarity in cells migrating on 2D surfaces is the emission of membrane protrusions in the form of broad lamellipodia and spike-like filopodia. Lamellipodia contain a highly branched dendritic network of actin filaments (red) whereas filopodia are formed by long parallel actin filament bundles. The acquisition of front-to-back polarity is controlled by small guanosine triphosphate (GTP)-binding proteins (small GTPases), such as Cdc42, Rac1 and RhoA, which regulate actin dynamics, adhesion organisation and the formation of lamellipodia and filopodia. Cdc42 is active towards the front of the cell and both inhibition and global activation of Cdc42 disrupt the directionality of migration. One main output of Cdc42 activity is the local activation of Rac1, and both proteins mediate actin polymerisation in protrusions. Once Rac1 and Cdc42 are active at the cell front, molecular feedback loops and mechanical tensile forces work together to maintain protrusions in the direction of migration. The back of the migrating cell is defined by the activity of Rho, myosin II and Ca<sup>2+</sup>-activated proteases. Active Rac1 at the cell front suppresses Rho activity whereas Rho is more active at the lateral and rear sides where it suppresses Rac1 activity. RhoA affects actomyosin contractility via Rho kinase (ROCK). In addition, strong adhesions at the cell rear result in increased tension, the opening of stretch-activated Ca<sup>2+</sup> channels, and the subsequent activation of proteases that have the potential to cleave focal adhesion proteins. (For reviews on the topic, see Li and Gundersen, 2008; Ridley et al., 2003.)
Once polarised, fibroblasts start moving in one preferred direction by repeated cycles of protrusion, adhesion to the substrate, contraction of the cell body, and rear retraction (Fig. 1A), as identified in the seminal studies by Michael Abercrombie (Box 2). Over time, the position of the dominant lamella changes and fibroblasts turn and move in new directions showing an overall random pattern of cell locomotion (Fig. 1B) (Bard and Hay, 1975; Trinkaus, 1969; Weiss, 1961). This ‘intrinsic’ tendency of the cell to develop multiple peripheral lamellae and exhibit random migration seems to depend on the total level of activated Rac, which translocates to the plasma membrane in its active form to induce actin polymerisation and lamellar extension. Accordingly, when plated on 2D surfaces, cells display relatively high levels of activated Rac, which promotes the formation of multiple peripheral lamellae and random migration (Fig. 1B) (Pankov et al., 2005). To overcome such intrinsic random motility and acquire directional migration, cells need to restrict protrusion formation to a single axial lamella. This can be achieved in 2D systems by lowering the total levels of activated Rac. Alternatively, moving cells from a 2D to a 3D culture environment can alter their intrinsic properties and behaviours (Pankov et al., 2005; Petrie et al., 2009) and can promote directional movements (for more details, see Box 3). However, as we discuss below, environmental guidance cues can also restrict protrusion formation and promote directional cell migration through the local activation of Rac.

**Box 2. Seminal contribution of Michael Abercrombie to the ‘cell migration cycle’**

In the early 1970s, Abercrombie, Heaysman and Pegrum performed a series of experiments that provided a basic framework for the study of cell migration. Fibroblasts were carefully examined as they migrated away from the edge of chick- and mouse-derived tissue explants onto a 2D glass surface, uncovering the presence of repeated cycles of membrane protrusion and withdrawal at the leading edge of migrating cells (Abercrombie et al., 1970a). Fluctuations in the position of these mobile sheet-like membrane projections, defined as lamellipodia, resulted in membrane ruffles that appeared primarily at the transitions between withdrawal and protrusion events, moving away from the leading edge towards the cell body (Abercrombie et al., 1970b). Although the rates of cell protrusion and withdrawal were similar, it appeared that the net forward movement resulted from the greater time that cells spent protruding (Abercrombie et al., 1970a). Furthermore, ultrastructural analyses revealed that lamellipodia exhibit discrete accumulations of dense material at sites of contact with the substrate, as well as intracellular longitudinal filaments that resembled actin cables (Abercrombie et al., 1971). This systematic description of the leading edge of a migrating cell raised the idea that substrate adhesion can provide a means of traction, which, together with contractile fibrils, allows the cell to pull itself forward. Together, these findings led to the proposal that cell migration is a cyclic process of protrusion, adhesion to the substrate, contraction of the cell body, and rear retraction (Abercrombie et al., 1971). During this cycle, cells require rapid insertion of new material at the leading edge (Abercrombie et al., 1970c, 1972), which allows the formation of new adhesions to the substrate and causes the excess to move backwards, giving rise to membrane ruffles.

**Guided in vitro cell locomotion**

ECM-mediated contact guidance

In early studies, Paul Weiss and co-workers observed that cells and axons seeded on 2D culture dishes elongate and migrate along topographical features of the substrate, such as engraved parallel microgrooves and oriented fibrillar structures (Weiss, 1945, 1959; Weiss and Taylor, 1956). This ability of cells to use the lack of homogeneity of the extracellular matrix (ECM) as cues to adhere, polarise and orient their migration was defined as ‘contact guidance’ (Fig. 2A) (Carter, 1965; Dunn, 1982; Weiss, 1961). Contact guidance has since been demonstrated in vitro for a wide variety of cell types (Dickinson et al., 1994; Dubey et al., 2001; Teixeira et al., 2003; Webb et al., 1995; Wood, 1988). Oriented features of the substrate, such as aligned ECM fibrils, can induce contact-guided behaviours by imposing geometrical constraints on cell-matrix adhesion sites and by providing physical cues to initiate polarisation of cell shape, orientation of cellular organelles and directional cell migration (Doyle et al., 2009; Loebsberg et al., 2007; Petrie et al., 2009; Weiss, 1945). In addition, tension imposed on the ECM (e.g. by substrate stretching) can align a random fibrillar meshwork and thus promote directed migration through a contact-guided mechanism (Fig. 2B).
Box 3. Cell migration in 2D versus 3D culture environments

When transferred from 2D (e.g. standard Petri dishes, glass coverslips) to 3D (e.g. gel matrix scaffolds, hanging drops) culture environments, fibroblasts change their shape, cell matrix adhesive structures and migratory behaviour (Bard and Hay, 1975; Elsdale and Bard, 1972; Pankov et al., 2005; Petre et al., 2009). Cells moving in 3D matrices become elongated and display more directional movements than those migrating on 2D surfaces. Such changes reflect distinct means by which migrating cells interact with the substrate and sense their physical properties (Garber, 1953; Weiss and Garber, 1952). Fibroblasts on 2D surfaces develop prominent and stable elongated focal adhesions, which associate with stress fibres over the broad lamellipodial region (Geiger and Yamada, 2011; Parsons et al., 2010). By contrast, the presence of focal adhesions in 3D environments is still a matter of debate (Fraley et al., 2010, 2011; Geraldo et al., 2012; Harunaga and Yamada, 2011; Kubow and Horwitz, 2011). An interesting observation is that adhesions similar to those found in 2D can be observed at the edge (but not at the centre) of the 3D culture dish, where the anchorage of collagen bundles to the culture dish increases the rigidity of the matrix and thus the tension experienced by cells (Fraley et al., 2011). Accordingly, cells plated on soft 2D substrates show irregular and unstable focal adhesions (Pelham and Wang, 1997) whereas adhesions similar in structure and molecular composition to those found in 2D can be detected in vivo in cells submitted to high tensile forces (Bokstad et al., 2012; Ralphs et al., 2002). These observations suggest that the formation and maturation of focal adhesions is sensitive to cellular tension and substrate stiffness (Kuo, 2013; Parsons et al., 2010). Cells migrating on 2D surfaces thus appear to form exaggerated versions of the adhesive structures found in vivo in cells submitted to elevated mechanical stress, whereas less rigid 3D matrices favour more discrete adhesions that seem to resemble those in most in vivo migrating cells. In the figure, labeled structures correspond to ECM fibrils (blue lines), stress fibers (green lines), focal adhesions (purple dots) and integrin heterodimers (pink/blue structures). A selected group of proteins forming the adhesion complex include Actinin, Tensin, Paxillin, Talin, Vinculin (Vinc) and Focal adhesion kinase (Fak).

Guidance by cell-cell contact

Cell-cell contact plays an instructive role in directing cell migration. This feature was noticed many years ago by Abercrombie and Heaysman when examining the behaviour of fibroblasts as they spread radially from culture explants and collided with fibroblasts that were moving in opposite directions from a confronted culture explant (Abercrombie and Heaysman, 1954). In events of cell-cell collision, fibroblasts exhibited a stereotypical behaviour whereby the cell front adhered to the colliding cell and experienced contraction and paralysis of protrusion and ruffling (Fig. 3A, B). Soon after, a new cell front was established away from the cell-cell contact zone and the collided cells (Nakatsuji and Johnson, 1984; Weiss, 1961). Alternatively, cells may by themselves align a random fibrillar meshwork (Harris et al., 1981; Stopak and Harris, 1982; Tranquillo, 1999) and thus assist their own directed migration along fibrillar structures (Fig. 2B). A clear example of the latter is observed in the case of epithelial tumour cells, which can align collagen fibres at the tumour-stromal interface to facilitate their local metastatic invasion (Provenzano et al., 2006, 2008). ECM-mediated contact guidance works as a mechanism that promotes oriented cell migration, but in principle it does not provide directionality (Fig. 2C) (Weiss, 1961). Additional cues must thus impose the directionality of migration (Fig. 2C). For example, cells showing contact-guided behaviour may direct their locomotion towards regions of increasing ECM deformation (Angelini et al., 2010; Reinhart-King et al., 2005) and rigidity (Lo et al., 2000). Similarly, gradients of surface-bound ligands can direct cell migration through a process of ‘haptotaxis’, which was initially described for cultured fibroblasts (Carter, 1965, 1967) and later extended to the oriented growth of axons on patterned collagen matrices (Letourneau, 1975) and of tumour cells along gradients of laminin (McCarthy et al., 1983). Finally, cell-cell contacts and polarised chemical signals (Fig. 2C) may direct contact-guided cell locomotion, and are discussed in turn below.

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moved apart (Fig. 3A,B) (Abercrombie and Ambrose, 1958). Such ‘contact inhibition of locomotion’ (CIL) (Abercrombie, 1970) was then reported in other in vitro contexts, such as when two epithelial sheets meet (Abercrombie and Middleton, 1968) and in the process of radial extension of nerve fibres (Dunn, 1971). In addition, CIL was observed during the migration of corneal fibroblasts in their natural stroma and in artificial 3D collagen lattices (Bard and Hay, 1975). Furthermore, CIL was proposed as an explanation for wound healing in epithelia (Abercrombie, 1970; Farooqui and Fentee, 2005) and for the invasive properties of certain malignant cells in vitro, movements of which were not restricted by contact with normal fibroblasts owing to defective CIL (Abercrombie, 1979; Vesely and Weiss, 1973).

CIL works to re-set the polarity of migrating cells. Cells initially sense contact with other cells either at the lamellipodium (Abercrombie, 1970; Abercrombie and Heaysman, 1954) or at longer distances through filopodial extensions (Carmona-Fontaine et al., 2008; Davis et al., 2012; Heckman, 2009; Lesseps et al., 1975; Stekete and Tosney, 1999; Teddy and Kulesa, 2004). Sensing is mediated by cell surface molecules, often cell-cell adhesion proteins of the cadherin family (Mayor and Carmona-Fontaine, 2010), which are proposed to change the balance in small GTPases, with local activation of RhoA at the cell-cell contact and suppression of Rac1 and repolarisation of the colliding cell (Nelson et al., 2004; Theveneau et al., 2010). When the sensing of cell-cell contact is perturbed, cells lose their ability to reset polarity and they produce numerous protrusions that are able to extend on top of neighbouring cells (Abraham et al., 2009; Theveneau et al., 2010; Villar-Cervino et al., 2013). Furthermore, the balance between CIL and attractive forces, which we discuss later, determines whether a group of cells disperses as individuals or as a collective group (Fig. 3C).

### Directed cell migration via chemotaxis

The ability of cells to undergo directed locomotion along a chemical gradient, a process known as chemotaxis (Fig. 4A,B), was first described in bacteria by Pfeffer (Pfeffer, 1884) and later in phagocytic leukocytes by Metchnikoff (Metchnikoff, 1893). Since then, chemotaxis has been a subject of intense research in both prokaryotic (Hazelbauer, 2012) and eukaryotic cells, including the free-living amoeba Dictyostelium discoideum, mammalian leukocytes, fibroblasts and neurons (Swaney et al., 2010; von Philipsborn and Bastmeyer, 2007; Vorotnikov, 2011). Despite exhibiting different modes of cell locomotion (ameboid in D. discoideum and leukocytes; mesenchymal in fibroblasts) and utilising different signal transduction mechanisms [G protein-coupled receptor (GPCR)-dependent in D. discoideum and leukocytes, and receptor tyrosine kinase (RTK)-dependent in fibroblasts], most in vitro models of eukaryotic chemotaxis share three general principles. First, cells often exhibit intrinsic random motility. Second, exposure to a chemoattractant gradient leads to small spatial or temporal differences in receptor activation that are amplified within the cell to induce Rac-mediated actin polymerisation and protrusion formation on the side of the cell facing the highest concentration of chemoattractant. Third, cell polarity is stabilised by positive-feedback loops (at the cell front) combined with long-range inhibitory signals (in the rest of the cell) that restrict protrusion formation towards the cell front and increase its sensitivity to chemoattractants along the gradient (Insall, 2013; Swaney et al., 2010; Vorotnikov, 2011; Wang et al., 2011). Under these general principles, there is major discussion concerning the mechanism by which receptor activation leads to the formation of polarised protrusions. The ‘chemotactic compass’ model (Fig. 4C, top) proposes that sensing of the gradient results in local accumulation of intracellular signalling molecules, such as phosphatidylinositol-3,4,5-triphosphate (PIP3), towards the highest chemoattractant concentration. Such localised signalling functions upstream of activated Rac and is used as a ‘compass’ to adjust the actual cell polarity by turning the cell front towards the gradient (Bourne and Weiner, 2002; Rickert et al., 2000; Swaney et al., 2010; Wang, 2009). The alternative ‘chemotactic bias’ model (Fig. 4C, bottom) proposes that chemoattractants simply bias the dynamic and self-organising autocatalytic nature of protrusions towards the gradient without the need of a compass (Arrieumerlou and Meyer, 2005; Insall, 2010). As such, this model seems to better integrate recent data showing that membrane tension resulting from actin polymerisation acts as a long-range physical signal that inhibits protrusion formation in regions other than the cell front (Batchelder et al., 2011; Houk et al., 2012). Although the compass and chemotactic bias models may differ in some aspects, it should be noted that they are not mutually exclusive and thus both probably operate in most eukaryotic cells (Insall, 2013).

### Mechanical guidance of cell locomotion

In addition to gradients in ECM rigidity, which are known to direct cell migration from soft to stiff substrates (Lo et al., 2000), it has recently been shown that physical forces applied at the cell-matrix and at cell-cell interfaces can also direct cell migration. For instance, cells migrating on soft ECM matrices may produce patterns of substrate deformation that serve as a cue to attract the migration of adjacent and distant cells (Angelini et al., 2010; Reinhart-King et al., 2005). In addition, cells forming a cohesive group can generate and sense gradients of intercellular tension to coordinate the direction of their collective migration (Tambe et al., 2011; Weber et al., 2012). These
Embryo development is a highly dynamic process during which cells and their environment are constantly changing and communicating. Embryonic cells can use either the ECM or other cells as substrates for migration, in contrast to the more typical ECM-mediated mode of cell locomotion observed in vitro. Furthermore, although cells can migrate as individuals they often move as collective groups during development, which imposes an additional challenge: to resolve whether guidance cues work at the individual or the collective group level. In this context, the complexity of developing systems challenges the ability to study guidance mechanisms as isolated entities and to address how different guidance strategies cooperate to generate in vivo patterns of cell migration. In this section, we examine how the aforementioned guidance principles of in vitro cell locomotion have been used to explain a number of in vivo events of directed cell migration during development (summarised in Table 1). We focus on developmental examples in which individual guidance mechanisms and cues have been dissected and explored to some extent. We also discuss the insights that emerge from these analyses, which provide us with clues as to how the migratory behaviours elicited by guidance mechanisms generate the stereotypical patterns of migration that shape developing tissues.

**Random cell motility during tissue morphogenesis**

Embryonic cells can activate random motility using various genetic signals, and this seems to be a prerequisite for initiation of directional migration in response to external guidance cues (Aman and Piotrowski, 2010). Random motility results in random patterns of cell migration, which per se can impact cell and tissue morphogenesis. In the context of individual cell migration, random motility has a dispersive and exploratory effect that prompts cells to colonise new territories within the embryo. Such an effect is characteristic of the early migratory phase of the zebrafish endoderm. During gastrulation, zebrafish endodermal cells disperse from the margin towards the animal pole following an intrinsic cell-autonomous ‘random walk’, which is characterised by the formation of short-lived small protrusions on cells in almost all directions (Fig. 5A, top) (Pezeron et al., 2008; Woo et al., 2012). This random migratory behaviour later switches to become persistently directed as endodermal cells start converging towards the midline in response to chemotactic cues (discussed below), while forming broader and more stable dorsally directed protrusions (Fig. 5A, bottom) (Pezeron et al., 2008; Woo et al., 2012). Random walking is induced by Nodal signalling at least in part through the expression of the Rac activator Prex1 (Woo et al., 2012): when Rac1 activity is disrupted, endodermal cells anticipate their dorsal-directed migration and, as a consequence, become mislocalised and in some cases fail to maintain their original fate to become mesoderm (Woo et al., 2012). These observations suggest that, in addition to its role in cell dispersion, random motility might also serve as a control mechanism for the response of the cell to guidance cues, generating a ‘noise’ that reduces the ability of cells to respond to weak environmental guidance cues that have the potential to interfere with their normal development (Woo et al., 2012).

When random motility occurs in gradients across developing tissues it may also serve to direct collective cell migration. Such a guidance role is observed during posterior elongation of the
Table 1. Summary of the guidance mechanisms of cell migration occurring during development

<table>
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<th>Model</th>
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Studies of urodele and anuran embryos have been performed with ECM fibrils on the blastocoel roof (BCR) of the amphibian gastrula (Wood and Thorogood, 1984), showing the migration of neuronal precursors along pre-existing neuronal/axonal and glial scaffolds in the brain (Fig. 6A). In addition, the migration of mesenchymal cells along collagenous unsegmented fibrils is known as actinotrichia in the developing teleost fin (Fig. 6A). These examples illustrate the variety of developmental contexts (Table 1).

Contact-mediated guidance can orient cell migration in a wide variety of developmental contexts (Table 1). Key examples include the migration of mesenchymal cells along collagenous unsegmented fibrils known as actinotrichia in the developing teleost fin (Fig. 6A) (Wood and Thorogood, 1984), as well as the migration of neuronal precursors along pre-existing neuronal/axonal and glial scaffolds in the brain (Fig. 6B). Studies of urodele and anuran embryos have been especially illuminating as they have combined in vivo observations with in vitro analyses of tissue explants and dissociated cells, and with molecular manipulations of cell-matrix interactions (Boucaut et al., 1991; Desimone and Johnson, 1991). During gastrulation in amphibians, the prospective head mesoderm migrates towards the animal pole using the inner surface of the epithelial ectodermal BCR as a substrate. Just before the onset of mesoderm migration, a fibrillar network of ECM fibrils forms on the BCR and becomes aligned along the vegetal-animal pole axis (Fig. 6C,D) (Nakatsuji et al., 1982; Nakatsuji and Johnson, 1983a). It was shown that dissociated mesodermal cells seeded on a plastic substrate that contains the ectodermal-derived fibrillar ECM network (obtained by previous conditioning with ectoderm explants) are able to attach and orient their migration along fibrils, as they do in vivo (Fig. 6E) (Nakatsuji and Johnson, 1983b). Importantly, if the ectodermal layer is artificially realigned by exerting mechanical tension in vitro (e.g., by tilting the substrate), the mesodermal cells also reorient their movements (Fig. 6F) (Nakatsuji and Johnson, 1984). Therefore, aligned ECM fibrils appear to orient mesodermal cell migration on the BCR through a contact guidance mechanism (Nakatsuji and Johnson, 1984). This mechanism appears to involve fibronectin (FN), which is a major component of the BCR fibrillar network (Boucaut and Darrubere, 1983; Davidson et al., 2004; Johnson et al., 1992); blockage of FN synthesis, function or fibrillar assembly, as well as abrogation of the integrin α5β1 receptor, leads to abnormal adhesion, spreading and migration of mesodermal cells (Boucaut et al., 1990; Darrubere and Schwarzbauer, 2000; Davidson et al., 2002; Nagel and Winklbauer, 1999; Rozario et al., 2009). Upon contact with FN, mesodermal cells relocate their intrinsic protrusive activity along the BCR surface and replace filopodia with lamelliform protrusions (Winklbauer and Keller, 1996; Winklbauer and Nagel, 1991; Winklbauer and Selchow, 1992). These results suggest that the FN-fibrillar network not only provides oriented adhesiveness and resistance to mesoderm cell traction but also regulates the protrusive activity of migrating cells. As described in vivo ECM-mediated contact guidance, the oriented migration of anterior mesodermal cells requires additional cues and factors to direct locomotion towards the animal pole, and these include CIL among mesodermal cells (Johnson et al., 1992; Winklbauer and Selchow, 1992) and attractive chemical signals produced by the BCR, such as the chemokine Cxcl12b (Fukui et al., 2007) and the ECM-bound platelet-derived growth factor A (PDGFA) (Nagel et al., 2004).

In addition to features of the ECM, cells can orient their migration by interacting with a cellular substrate. Such cell-cell mediated contact guidance is observed during the migration of neuronal precursors along pre-existing neuronal/axonal and glial scaffolds in the developing and adult brain, in processes referred to as ‘neurophilic’/axonophilic’ and ‘gliophilic’ cell migration, respectively (Table 1). For example, gonadotropin-releasing hormone (GnRH) neurons migrate from the nasal placode towards the olfactory bulb region (Fig. 6B). The GnRH neurons follow vomeronasal axons and this event is mediated by cell-cell interactions involving integrin β1 (expressed in GnRH neurons) and the glycoprophatidylinositol (GPI)-linked semaphorin 7A (expressed in axons) (Cariboni et al., 2007). However, contact with the vomeronasal axons only provides orientation, and the nose-to-brain directionality of GnRH neuronal migration depends on a chemotactic gradient of semaphorin 4D (Fig. 6B) (Messina and Giacobini, 2013).

Cell-mediated contact guidance is also observed in Caenorhabditis elegans and Drosophila primordial germ cells. These cells are quiescent and establish E-cadherin-mediated adhesive interactions with the endoderm, and as the endoderm moves they are carried along...
by a ‘hitchhiking’ mechanism (Chihara and Nance, 2012; DeGennaro et al., 2011). Importantly, contact-guided cell migration can be regulated by switching the adhesion efficiency and/or by changing the way that cells interpret the landscape along their route of migration. For example, distal tip cells in the C. elegans gonad show an initial phase of directional migration that is driven by the integrin INA-1 α subunit which is followed by an arrest in cell migration after switching integrin receptor expression from INA-1 α to PAT-2 α (Meighan and Schwarzbauer, 2007, 2008). Similarly, GnRH neurons transform their early directional migration along vomeronasal axons into a state of decreased attachment and spreading by switching integrin β1 to plexin C1 after crossing the nasal-forebrain border (Fig. 6B) (Messina and Giacobini, 2013). As haemocytes contact each other, a stable arm-like microtubule bundle that extends into the lamellae collapses, enabling cell repulsion, turning and dispersion (Stramer et al., 2010). In other contexts, cells undergoing CIL do not disperse but instead organise as a cohesive cluster owing to additional forces that restrict cell dispersal. For instance, mesenchymal cells moving by CIL organise in collective migratory streams owing to attractant cues that the cells themselves produce and sense. For example, the cohesive migration territories starting from confined regions of the embryo (Table 1). For example, Drosophila haemocytes, attracted by a source of the Drosophila platelet-derived growth factor (PDGF)/vascular endothelial growth factor (VEGF) ligand PVF1, migrate from the head mesoderm to form a linear cellular array at the ventral midline (Cho et al., 2002; Wood et al., 2006), and from this position they disperse laterally to form a ‘three-lined’ organisation pattern as a result of CIL (Fig. 7A) (Davis et al., 2012; Stramer et al., 2010). As haemocytes contact each other, a stable arm-like microtubule bundle that extends into the lamellae collapses, enabling cell repulsion, turning and dispersion (Stramer et al., 2010). In other in vivo contexts, cells undergoing CIL do not disperse but instead organise as a cohesive cluster owing to additional forces that restrict cell dispersal. For instance, cell-cell adhesive interactions keep epithelial cells together during collective migration driven by CIL, as observed in the movement of Xenopus pre-placodal cells (Theveneau et al., 2013). By contrast, mesenchymal cells moving by CIL organise in collective migratory streams owing to attractant cues that the cells themselves produce and sense. For example, the cohesive migration
Retzius cells (Fig. 7C) (Villar-Cervino et al., 2013). Finally, external endodermal cells (Fig. 5A) (Pezeron et al., 2008) and mouse Cajal-triggered by CIL, also observed di in the developing neocortex. The proposed mechanisms of CIL are depicted below each example. In haemocytes, CIL involves a collision of lamellae containing conspicuous arms of microtubule bundles (red lines) that disassemble upon cell-cell contact to enable cell repulsion and turning. Neural crest and Cajal-Retzius cells form highly dynamic membrane processes that retract or are repulsed upon cell-cell contact, after which cells repolarise and move away from the cell-cell contact zone. Cell retraction/repulsion is mediated by N-cadherin adhesive interactions and downstream RhoA activation in neural crest cells, and through Ephrin/Eph bidirectional signalling in Cajal-Retzius cells.

of *Xenopus* neural crest cells (NCCs) (Fig. 7B) is favoured by the C3a complement immune-derived component, which is produced by NCCs and works as an attractant cue for the same cells (Carmona-Fontaine et al., 2011). When NCCs contact each other within the cluster, cell-cell contact mediated by N-cadherin triggers a repulsive response by activating RhoA at the contact site, leading to cell repolarisation and promotion of cell dispersal (Carmona-Fontaine et al., 2008). Therefore, NCCs within the collective migratory group are not static but they constantly split, collide and reassemble, showing cryptic protrusions when in inner positions but a strong front-to-back polarity if placed at the free edge of the cluster (Carmona-Fontaine et al., 2008, 2011; Théveneau et al., 2010). Importantly, cells that in the embryo normally migrate as a cohesive group (e.g. NCCs) can disperse as individuals if the forces of attraction are inhibited, whereas the induction of attraction among embryonic cells that normally disperse (e.g. myeloid cells) results in the formation of cohesive migratory streams (Carmona-Fontaine et al., 2011). These findings indicate that cells undergoing CIL are able to switch between individual and collective migratory behaviours according to the balance of attractive and repulsive interactions that they experience (Fig. 3C). When the balance favours repulsive interactions, CIL leads to cell dispersal. By contrast, migratory cells organise as a cohesive group when attractive forces become dominant.

Cell-cell contact repulsive interactions triggered by CIL seem sufficient to generate self-organised patterns of individual and collective cell migration, and the random versus directional nature of this migration is determined, at least in part, by factors that influence the rate and spatial organisation of cell-cell collision events, such as cell density, cell shape and the geometry of the substrate (Abercrombie and Heaysman, 1954; Bindschadler and McGrath, 2007; Carmona-Fontaine et al., 2011; Coburn et al., 2013; Costa et al., 2008; Davis et al., 2012; Lesseps et al., 1979; Villar-Cervino et al., 2013). In addition, intrinsic random motility may favour stochastic cell dispersal triggered by CIL, as observed in the ‘random walk’ of zebrafish endodermal cells (Fig. 5A) (Pezeron et al., 2008) and mouse Cajal-Retzius cells (Fig. 7C) (Villar-Cervino et al., 2013). Finally, external guidance cues such as the chemokine Cxcl12 may be integrated into the CIL process to either restrict CIL events within defined spatial domains (Borrell and Marin, 2006) or promote directed cell migration by enhancing the polarity induced by CIL (see next section).

**Guidance by chemotactic signals in developing systems**

Chemotaxis works as a guidance mechanism for individual and collective cell migration in a variety of developmental contexts (Table 1). Among the best-studied examples are the individual cell-based migration of zebrafish primordial germ cells, the epithelial cluster-based migration of *Drosophila* border cells and of the zebrafish posterior lateral line primordium, and the mesenchymal collective-based migration of *Xenopus* cephalic neural crest cells (Fig. 8) (Aman and Piotrowski, 2010; Montell et al., 2012; Rørth, 2002; Tarbashevich and Razo, 2010; Théveneau and Mayor, 2012). These *in vivo* examples share two main principles of chemotaxis. First, intrinsic random cell motility is present before exposure to a chemoattractant gradient. Indeed, genetic pathways that are independent of chemotaxis trigger random cell motility, and this appears to be a pre-requisite for initiating directional migration in response to chemoattractants. Second, exposure to a chemoattractant gradient activates receptor-mediated signalling that biases the intrinsic random cell motility towards the gradient by directing front-to-back polarity, stabilisation of cellular protrusions and cell translocation. Consistent with these observations, both the abrogation of receptor-mediated signalling and the exposure to homogeneous chemoattractant concentrations impair directional cell migration in the same way, resulting in random polarity and protrusion formation without affecting motility per se. Below, we discuss each of these developmental examples of guidance by chemotactic signals in turn.

Zebrafish primordial germ cells (z-PGCs) migrate as individuals from their site of specification towards the future gonad (Fig. 8A, top) displaying a unique mode of intrinsic locomotion that is characterised by alternating phases of persistently directed migration (‘run’) and pauses (‘tumbling’) (Reichman-Fried et al., 2004), which resemble the biphasic chemotactic behaviour of nerve growth cones (Ming et al., 2002). During ‘runs’, z-PGCs form spherical
blebs that are propelled by RhoA-mediated myosin II cortical contraction and hydrostatic pressure, which result in a retrograde flow of cortical actin. This event is modulated by chemokine signalling, specifically Cxcr4b receptor activation by a gradient of Cxcl12a, which induces local amplification of intracellular Ca\(^{2+}\) influx at the cell front resulting in enhancement of RhoA-mediated
myosin II contraction, stabilisation of cell protrusions and increase in the time spent in ‘runs’ (Blaser et al., 2006; Kardash et al., 2010; Reichman-Fried et al., 2004). Traction forces for cell translocation are generated by linking the retrograde actin flow to E-cadherin (also known as Cadherin 1)-mediated adhesions with somatic cells (Fig. 8A, bottom) (Blaser et al., 2006; Kardash et al., 2010). Such behaviour differs from the most common mode of locomotion in which cells move by forming protrusions through Rac-mediated actin polymerisation at the front (Box 1).

Drosophila border cells (d-BCs) are organised as a cluster of six to eight epithelial cells that migrates from the anterior follicular epithelium towards the oocyte in two distinct phases that require attachment to a cellular substrate through E-cadherin (also known as Shotgun) (Fig. 8B, top) (Niewiadomska et al., 1999; Pacquelet and Rørth, 2005). In the early phase (Fig. 8B, middle), d-BCs emit long and stable extensions that firmly attach to nurse cells and allow the cluster to be pulled forward in a highly directional manner through actomyosin contraction (Bianco et al., 2007; Fulga and Rørth, 2002; Poukkula et al., 2011). In the late phase (Fig. 8B, bottom), the BC cluster adopts a round shape and moves with less directionality, and cells exchange positions and form short and unstable extensions with a front bias (Bianco et al., 2007; Poukkula et al., 2011). During these events, d-BCs use two RTKs to sense chemotaxants, although the PVF1 receptor PVR has a dominant role in the early migratory phase whereas EGFR (and its ligand Gurken) takes over at later stages to allow the final dorsal migration (Duchek and Rørth, 2001; Duchek et al., 2001; Poukkula et al., 2011; Prasad and Montell, 2007). Both receptors utilise different effector proteins and guidance strategies, which are based on the subcellular localisation of signalling within the leading cell (in the case of PVR) and differences in signal levels among the constituents of the cluster (in the case of EGFR) (Assaker et al., 2010; Bianco et al., 2007; Janssens et al., 2010; Jekely et al., 2005; Ramel et al., 2013). However, signalling seems to converge on Rac activation, as focal photoactivation of Rac is sufficient to direct protrusion formation and rescue directional migration of the entire cluster when PVR and EGFR function are disrupted (Wang et al., 2010).

The zebrafish posterior lateral line primordium (z-pLLP) is organised as a cohesive cluster of >100 cells that migrate from the otic placode towards the tail following the horizontal myoseptum (Fig. 8C, top). The z-pLLP shows clear group polarity, displaying more extensive protrusions at the front than at the back of the cluster (Haas and Gilmour, 2006). Mosaic genetic analysis revealed that individual cells containing a functional chemosensing receptor adopt a front position within a cluster lacking the receptor, and are able to rescue migration of the entire primordium (Haas and Gilmour, 2006; Xu et al., 2014). This is similar to the behaviour observed in the early phase of d-BC migration (Bianco et al., 2007), indicating that in both developmental contexts the activity of front cells is fundamental for cluster migration. Chemokine signalling is also involved in z-pLLP migration; Cxcl12 is a major chemotaxant, and graded activation of Cxcl12/Cxcr4b signalling, which decreases from front to back, results in enhanced actin dynamics and the stabilisation of protrusions towards the front of the cluster (Fig. 8C, bottom) (Dona et al., 2013; Venkiteswaran et al., 2013; Xu et al., 2014).

Xenopus neural crest cells (x-NCCs) also migrate as a collective group, from the dorsal neural tube to lateral and ventral regions of the embryo (Fig. 8D, top). The traction forces for NCC locomotion are generated by cell protrusions that adhere to the ECM (Theveneau et al., 2010). Furthermore, x-NCCs coordinate their directed movements by combining CIL with chemotaxis. As previously described, the collective movement of NCCs away from the dorsal neural tube is directed by both CIL and ‘co-attraction’ among NCCs, which induces cell polarisation and protrusion formation towards the free edge of the collective cell group (Carmona-Fontaine et al., 2008, 2011). As NNCs migrate, they also sense a source of the chemotaxant Cxcl12, which is produced by epithelial epibranchial placodal precursors (EPPs), and they respond to this cue by enhancing the polarity induced by CIL (Theveneau et al., 2010). Bidirectional interactions between NCCs and EPPs direct the coordinated migration of both cell populations towards lateral and ventral regions (Fig. 8D). NCCs are attracted by Cxcl12 produced by EPPs (‘chase’) and, as both cell types make contact, EPPs move away from NCCs through CIL (‘run’), leading to forward displacement of the Cxcl12 source and the engagement of both NCCs and EPPs in repeating cycles of ‘chase-and-run’ behaviour (Fig. 8D, bottom) (Theveneau et al., 2013).

Shaping chemotaxant gradients in vivo

As highlighted above, cell migration during development is often dependent on gradients of chemotaxants, and studies have shown that embryonic cells use different strategies to shape these chemotaxant gradients in vivo. Chemotaxants may be produced in discrete spatial domains and from there diffuse and exert their graded effect over a long distance, as seen in the Drosophila egg chamber where PVF1 is produced at the posterior pole and attracts d-BCs located at the anterior pole (Fig. 8B) (Duchek et al., 2001). It is also possible that a stable gradient of immobilised chemotaxant is formed after diffusion, as observed for the mouse chemokine CCL21, which is released by lymphatic vessels and attracts dendritic cells through a decay-mediated gradient of CCL21 bound to heparan sulfates (Weber et al., 2013). In addition, chemotaxants may work over a short-distance. For instance, the Drosophila FGF Branchless is expressed in focal domains surrounding the developing tracheal system and exerts a local guidance effect that directs branch formation (Sutherland et al., 1996). Similarly, x-NCCs exhibit short-range attraction to a moving source of Cxcl12 produced by pre-placodal cells, from which they never seem to distance themselves due to a ‘chase-and-run’ behaviour (Fig. 8D). However, embryonic cells may also move directionally along stripes of homogeneously produced chemotaxants, and for this to occur they require an active way to shape the gradient. The principle of such a mechanism resembles the source-sink model (Crick, 1970) and relies on the asymmetric removal of chemotaxants from the extracellular space by receptor-mediated endocytosis, which can be performed either by cells forming the substrate of migration or by the migrating cells themselves. An example of the former is observed during the guidance of z-PCGs when a functional Cxcl12a gradient is shaped by somatic cells through Cxcr7-mediated endocytosis (Boldajipour et al., 2008). However, embryonic cells may by themselves generate a chemotaxant gradient as they migrate, as demonstrated in vitro for cancer cells in 3D matrices (Shields et al., 2007) and for epithelial cells using microscale engineering techniques (Scherber et al., 2012). Cells in the z-pLLP also promote their own directional migration along the horizontal myoseptum through polarised Cxcr7-mediated endocytosis of Cxcl12a at the back of the cluster, which generates a functional linear gradient of Cxcl12a/Cxcr4b signalling across the migrating primordium that increases towards the front (Fig. 8C) (Danby-Chaudiere et al., 2007; Dona et al., 2013; Valentin et al., 2007; Venkiteswaran et al., 2013). Such a self-generated strategy for guiding cell migration differs from classical chemotaxis as it predicts that, once formed, the gradient will continually move with cells and will lock them in a persistent migratory phenotype until they encounter a stop signal (or lose polarity).
Directed cell migration by long-range tissue deformation

Recent in vivo studies have shown that the ECM itself displays tissue-level movements that have been suggested to direct cell and tissue locomotion (Aufschnaiter et al., 2011; Benazeraf et al., 2010; Czirok et al., 2004; Filla et al., 2004; Zamir et al., 2006, 2008). For example, during avian gastrulation the epiblast and the underlying sub-epiblastic ECM move together as a tissue composite (Zamir et al., 2008) and similar large-scale coordinated movements are observed among mesodermal cells and their surrounding ECM (Czirok et al., 2004; Zamir et al., 2006). In both cases, the directed composite movements are proposed to be driven by both long-range mechanical forces, which are transmitted from global embryo morphogenesis into large-scale ECM flows, and by cell-autonomous migratory activities (Benazeraf et al., 2010; Zamir et al., 2008). Although the mechanism of force transmission is yet to be elucidated, these findings challenge our view of how guidance mechanisms based on chemoattractant gradients and cell-cell contacts operate in developmental contexts in which cells and the ECM move together as a composite.

Conclusions
Here, we have reviewed how the main guidance principles of in vitro cell locomotion apply to defined developmental contexts in a variety of vertebrate and invertebrate model organisms. Embryonic cells transit between mesenchymal and epithelial states, and in both conditions they must trigger motility to initiate random or directional migration. Intrinsic random motility is observed in the absence of guidance cues, when cells are unable to sense these signals, and in the presence of homogeneous (non-graded) levels of guidance cues. This random cell motility has a morphogenetic role per se by promoting cell dispersion or, if spatially organised, by coordinating the migration of collective cell groups. However, migrating cells can also follow topographical features of the substrate through contact guidance and, in these situations, the directionality of movements is provided by additional chemical or physical cues. Such guidance cues normally bias random cell motility towards a polarised source of the signal or, in the case of gradients, towards the highest or lowest concentration of the signal. Motility bias relies on the induction of front-to-back cell polarity, which involves actin polymerisation at the cell front and the stabilisation of protrusion formation towards the signal. These events are frequently mediated by signal transduction events downstream of receptor activation that modulate the activity of small GTPases and actin dynamics. The transmission of membrane tension across the migrating cell also plays an instructive role in directing polarised motility. All the aforementioned processes show tight genetic regulation during development with respect to both the timing of cellular events and the spatial configurations of environmental signals. Such genetic control pre-configures the substrate landscape and determines the possible response mechanisms that cells can activate to direct their migration. However, migrating cells can also self-organise the chemical and physical substrate to which they will respond (e.g. by self-generating a chemoattractant gradient). In addition, cells can generate patterns of migration through interactions with other migrating cells (e.g. by means of contact inhibition of locomotion). The latter migratory events are not pre-configured and thus represent emerging properties of the system. Further studies exploiting the advantages offered by model organisms for embryo and tissue handling, optical imaging and genetic manipulation, will provide novel insights into how chemical and physical signals are integrated with intrinsic cellular properties to produce stereotypical and robust migratory responses. This task is especially crucial for the guidance of collective cell groups, which is the most common way of locomotion during critical stages of development.

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References


Garber, B. (1953). Quantitative studies on the dependence of cell morphology and motility upon the fine structure of the medium in tissue culture. Exp. Cell Res. 5, 132-146.


