

**From reasoning and intelligence research to information design:  
Understanding and optimising the usability  
and acceptability of schematic transit maps**

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**Running Head: Schematic transit maps**

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**ABSTRACT**

For over 100 years, cartographers and graphic designers have attempted to simplify the depiction of transit networks by converting complex meandering trajectories into straight lines, with surface details absent if they are irrelevant to journey planning. Spurred on by the practical and popular success of the London Underground diagram (whose basic design principles were first introduced by Henry Beck in 1933), such depictions are now ubiquitous, and generally adhere to the London standard design rules, with horizontal, vertical, and 45 degree diagonal lines. However, emulation of the success of London has been mixed. In this chapter, I argue that schematic maps are misunderstood by many designers, leading to poorly optimised results, and that the situation is exacerbated by a low correlation between subjective evaluations of design effectiveness, and objective measures of actual usability. This dissociation is easily understood within the context of psychological findings concerning metacognition, expert-novice differences in problem solving, and expectations and prejudices. Findings from the intelligence testing and reasoning literatures point towards general principles for effective design in terms of provision of supplementary information and line configurations, and a framework for this is proposed.

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Any travel by public transport, anywhere in the world, will almost certainly result in an encounter with some sort of schematic map, either for planning a journey, assisting in locating the correct departure point, or confirming the status of a journey en route. This method of information presentation can be amongst the most complex that members of the public are likely to be expected to use in everyday life. Indeed, with ever-increasing network complexity worldwide, a recent mathematical analysis (Gallotti, Porter, & Barthelemy, 2015) suggests that there is a cognitive limit to the understandability of complex transport networks, and a number of these worldwide have already exceeded this.

Typically, schematic maps are highly stylised, with routes shown as straight lines – horizontal, vertical, or 45° diagonals – joined by tightly radiused corners. Mathematically, this is known as an *octolinear* design. Topography may be considerably distorted, and most, if not all, surface details omitted, so that the focus of such designs is on the routes, stations, and inter-connections between lines. Famously, Henry Beck's diagrammatic London Underground map, first published in 1933, adopted these principles, and they have been applied to almost every London design since (Garland, 1994; Roberts, 2005). With time, schematic maps have become particularly associated with urban rail networks worldwide (Ovenden, 2015).

For transport undertakings that publish a schematic network map, the belief is clearly that this will offer a simplified version of reality, improving usability compared with a fully-detailed topographic map drawn to scale. Hence, the use of public transport is facilitated and encouraged. However, few cities have managed to emulate the success of the London version, which has been asserted to be a design classic, and voted one of Britain's most iconic creations (*BBC Television*, 1987, 2006). Indeed, public responses to some international works indicate that the creation of a genuinely successful design is not easily achieved. One of the most famous failures is the Vignelli New York Subway diagram. Introduced in 1972 to critical acclaim (a copy is held in the collection of the New York Museum of Modern Art), it became

the victim of campaigners who claimed that its abstractedness disconnected New Yorkers from their city. It lasted just seven years, and was withdrawn in 1979, replaced by a map that sought to show topographical reality more accurately, along with more surface features (Lloyd, 2012). In Madrid, a controversial design introduced in 2007 generated considerable debate (e.g., Engel, 2007). It was intended to be compact, but depicted the network as a severe grid using just horizontal and vertical lines (technically, a *tetralinear design*) along with considerable topographical distortion and crushed suburbs. In both these cases, the supposed benefits of the schematic depiction were judged by users to be outweighed by the topographical distortion and abstractedness of the designs. The London Underground map ran into a similar problem in 2009 where, in an attempt to simplify it still further, the River Thames was removed. This made news and television headlines (e.g., *Daily Mail*, 2009) and the river was reinstated soon afterwards.

The Paris Metro is another example of a schematic map that does not fulfill its full potential. The system is a challenge to show clearly, with a dense network of interconnected lines that follow complex twisting trajectories. Network expansion from the 1960s onwards put the established design under considerable pressure, and the rapidity with which new routes were constructed caused unprecedented design instability, with numerous different solutions attempted (Ovenden, 2009). The current official version, first released in 2000, adopted conventional octolinearity, but here the problem is different. Roberts et al. (2013) argue that the complex line trajectories of the schematic do little to simplify the depiction of the network compared with topographical reality, merely converting twisting turning lines into zigzags instead, so that the map changes the shape of the complexity rather than reduces it. They compared the official map with a novel curvilinear design, and found that this had considerably improved times for planning journeys between pairs of stations, compared with the official version.

The contrasting situations in London, New York, Madrid, and Paris highlight that the design of an effective schematic map that is genuinely easy to use, and is accepted by the general public, is not simple to achieve. There are usability issues that have to be addressed, and users

have expectations that should be satisfied, within reason. Furthermore, different cities have gravitated towards different solutions (schematic versus topographical) and different degrees of topographical distortion for their schematic maps (high for London, low for Paris). It is noteworthy that users tend to object to certain adverse aspects of design (abstractedness, topographical distortion) but others tend to go unnoticed (e.g., failure to simplify line trajectories). This can be demonstrated strikingly in usability studies, where objective measures of planning times are recorded along with subjective measures (either questionnaire ratings of map usability, or choice tasks where users are asked to select a preferred design). The subjective measures are correlated (e.g., Roberts et al., 2013) but the correlation between subjective and objective measures is effectively zero. Hence, people often choose maps that they find difficult to use, and reject maps that they find easy to use.

Psychologists will not be surprised by a dissociation between objective measures of design effectiveness, versus subjective evaluations of this. Such metacognitive failures have been observed for decades (e.g., Chabris & Simons, 2010; Kruger & Dunning, 1999). Often, the problem is that there are limited cues to whether performance is successful or not. Provided this is reasonably competent, and errors are few, then subtle cues, such as a tendency for a persistent difference between tasks of a few seconds, will simply be insufficiently salient, especially as self-monitoring is itself a task that demands cognitive resources (e.g., Dierckx and Vandierendonck, 2005). Without salient performance cues, and given that most users will not be experts at visual information design, it is inevitable that maps will be evaluated according to their superficial surface properties (e.g., *are there significant topographical distortions?*) rather than the more subtle aspects of design that contribute more directly to usability – this tendency by novices has been observed for decades (e.g., Chi, Feltovich & Glaser, 1981). Roberts (2014b) reports a preliminary analysis of an internet-administered map rating task. People were asked to look at nine different versions of the London Underground map, and rate the usability of each one. One important finding was that there was a massive *octolinearity bias* in ratings, even for designs deliberately intended to be difficult to use. All octolinear maps were given ratings which were considerably inflated relative to matched versions using different design rules; favourable ratings that were not warranted given either

actual or predicted usability data. This bias is not surprising considering the ubiquitousness of octolinearity worldwide. As per the mere-exposure effect (e.g., Bornstein, 1989), familiarity results in a more positive evaluation for maps designed in this way, compared with less conventional ones. With repeated exposure, people therefore develop opinions about the correct way to design a schematic map, and these expectations and prejudices will dominate their subjective evaluations. Objective measures and subjective evaluations will only be correlated if performance differences between designs are sufficiently large and salient to override expectations. Alternatively, the illusion of a correlation can be created in a case where a disliked aspect, such as noticeable topographical distortion, is by chance correlated with a more fundamental design weakness, such as complex line trajectories.

Of course, user acceptance is an important aspect of design. An impeccably effective map will have failed if people nonetheless reject it. The problem is that there are considerable individual differences in subjective evaluations – presumably the designers of the Madrid, New York, and Paris maps were pleased with the results, and the London officials responsible for removing the River Thames thought that this would be a useful change. Looking at actual data, the curvilinear Paris Metro map (Roberts et al., 2013) is a more effective design than the official octolinear version, but is only chosen by around half the sample in usability studies, even when all people have experienced both maps. This figure reflects not only a failure of metacognitive monitoring, with expectations and prejudices overruling usability observations, but also considerable individual differences in map preference, with half of the sample prepared to put a conventional design to one side, preferring a radical alternative instead.

### **Conjectures, prescriptions, and frameworks for effective design**

The dissociation between subjective evaluations and objectively measured performance means that the selection of new designs should always be based, at least in part, on usability testing, especially where departures from convention are being proposed. The general public cannot be blamed for their octolinearity bias, this is a natural consequence of their cognitive make-up. However, a more explicit bias; amongst graphic designers, transport officials, researchers, and commentators – the *octolinearity as a gold standard conjecture* – is less

defensible. This is the widespread assertion that applying *octolinearity* will result in the best schematic map possible, no matter what the structure of the network (e.g., Ovenden, 2005, p. 39). For example, until recently, this dictated the objectives of researchers attempting to automate schematic map design, so that Nöllenburg & Wolff (2011) described octolinearity as a *Hard Constraint* (i.e., it should never be broken) and suggested that “the main benefit of octilinear layouts is that they potentially consume less space and use fewer bends while still having a tidy and schematic appearance” (p. 626) and that “we believe that octilinearity, which is strictly followed by most real metro maps, is an essential ingredient for tidy and easy-to-read metro map layouts” (p. 627). It is also worth noting that, irrespective of technology through the ages, an octilinear design has always been easier to create than alternatives, so that ease of implementation may be partly responsible for this design bias.

Roberts et al. (2013) criticise the *octolinearity as a gold standard conjecture* from a number of different viewpoints. First, they note that there is very little in the psychological literature that can predict or corroborate it. Second, a belief in this conjecture discourages consideration of the possibility that networks with different structures may require different design solutions, and also deflects from analysing maps from the perspective of the quality of implementation within the design rules adopted: Many designers appear to believe, as evidenced in their products, that simply creating an octilinear diagram is a pathway to outstanding usability. This is not the case, and a poorly-executed creation can easily result. Third, the superiority of the curvilinear map versus the official octilinear design demonstrated by Roberts et al. (2013) conclusively disproves the *strong* version of the conjecture (octolinearity will *always* result in the most effective design) although weaker versions are left intact (e.g., octolinearity will *usually* result in the most effective design, but not in instances where this is incompatible with network structure).

Roberts (2012) notes that octolinearity is just one of numerous angle-sets that could be used for schematic maps. In other words, the *level of linearity* can be varied. Hence, a design might use just two perpendicular angles (tetralinear), three angles at 60° to each other (hexalinear), four angles (octilinear), five angles (decalinear) and so on. A systematic and exhaustive

exploration of these is suggested for any city whose network is to be mapped, and Roberts (2012) implements this for Berlin and London. The aim of this procedure is for the designer to specify the objectives for a design in advance, and then identify the level of linearity that best-enables these to be met. However, precise guidance on design objectives is remarkably rare (Roberts, 2014b). Nöllenburg (2014) gives a substantial set (e.g., keep line trajectories as straight as possible, space stations evenly, station labels should not occlude lines, and relative positions of stations should be preserved). Ovenden (2009) provides a collection that is broadly compatible, but includes more subtle prescriptions (e.g., do not bend a line twice between a pair of stations, keep station labels horizontal) that may be more likely to affect aesthetic judgement than actual usability. Many of these prescriptions seem reasonable, and can shown to be compatible with theories of human cognition (see later) but there is surprisingly little empirical evidence to demonstrate their efficacy (Roberts, 2014a). They form a somewhat disparate set of principles, not necessarily compatible with each other, and Roberts (2012, 2014b) therefore attempted to organize these into a broad framework of five categories.

*Simplicity.* The key-most requirement for a schematic map is that it converts the complex trajectories of routes into simple line trajectories on the diagram. Many designers appear to neglect or misunderstand this criterion, and in the process convert the complex line trajectories of reality into numerous short zig-zagging segments, despite the questionable utility in terms of information value.

*Coherence.* The *simplicity* criterion refers to individual line trajectories. The way these relate together to give the design overall *good shape* is also important, but harder to define and measure. Objectives can be specified that will contribute to coherence, such as maximizing parallel lines, symmetrical divergence of branches, and aligning stations and termini. Coherence might also be achieved by emphasizing regular, easily identified shapes, such as circles, equilateral triangles, horizons (grounding the design using horizontal lines) and/or grids.



*Balance.* Ideally, there should be an even density of stations across a map, or at least gentle density gradients, so that congested areas and empty spaces are not directly adjacent. The natural consequence of attempting to create a balanced design for an extensive network with a clear central region is that the centre will be enlarged and the suburbs compacted. An over-enlarged centre with over-compressed suburbs, however, can lead to a diffuse design without a clear attentional focus.

*Harmony.* Roberts (2012, 2014b) suggests a placeholder category for design aspects that are likely to influence aesthetics, but are unlikely to have any measurable impact on usability. There will be individual differences in this respect, but research does suggest that certain shapes and patterns tend to be rated as being more pleasing than others (e.g., Lindell & Mueller, 2011). For example, line crossings at 90° might be preferred to non-perpendicular ones, and equilateral triangles preferred to narrow pointed isosceles ones.

*Topographicity.* In order to optimize a design according to the above criteria, topographical distortion is inevitable to at least some extent. A schematic with poor topographicity is one in which distortion is sufficiently extreme that it adversely affects user-confidence – as a result of significant conflicts with mental models of a city – or worse, leads to the planning of inefficient routes. For example, Guo (2011) looked at actual journeys taken on the London Underground, and found that for one region of the map, with poor topographicity, inefficient journeys were taken 30% of the time. Vertesi (2008) describes how Londoner's understanding of the structure of the city has been distorted by their knowledge of the London Underground map. One consequence of this is that users may take unnecessary journeys owing to exaggerated distances between stations implied by the current official design.

There are two key aspects to note about this framework. First, it is neutral in terms of the actual design rules. As long as the framework criteria are satisfied, the rules do not matter, so that a requirement for octolinearity is not specified. The second aspect is that the criteria are often in conflict with each other. For example, using many more angles than the four permitted by octolinearity will permit simpler, straighter line trajectories, but at the expense of the coherence of the design. Alternatively, straightening octolinear line trajectories may

damage topographicity. Therefore, empirical testing is important not just to demonstrate the necessity of each of these criteria, but also to prioritise them. However, in lieu of this, showing that these components are compatible with the literature on reasoning and intelligence at least gives them a plausible initial foundation

### **Embedding map design prescriptions in theories of reasoning and intelligence**

For a reasoning researcher attempting to get to grips with a problem from the real world, there is a considerable body of established theories and findings to draw upon, derived from a variety of domains and tasks. The circumstances in which people succeed or fail in their attempts to make inferences are well-documented and understood, and researchers can easily manipulate task structure with predictable consequences for individual item difficulty (e.g., Evans, Newstead, & Byrne, 1993; Manktelow, 2012). Underlying these effects is usually the working memory load of a task. The more mental steps necessary for completion, the harder any task will be (e.g., Birney & Halford, 2002; Roberts & Sykes, 2005). The effects of task format on performance can also be considerable: Manipulations can be easily performed that hinder or facilitate identifying and representing the underlying logic of a task, with an imperfect representation increasing the working memory load (e.g., Meo, Roberts, & Marucci, 2007; Roberts, Welfare, Livermore, & Theadom, 2000). Mitigating against these manipulations, to at least some extent, are the effects of individual differences in intelligence and expertise, the former influencing the extent to which performance is degraded by high working memory demands (e.g., Carpenter, Just, & Shell, 1990; Stanovich & West, 1998), the latter whether efficient problem representations can be developed even when camouflaged by the surface structure of a problem (e.g., Chi, Feltovich, & Glaser, 1981).

For schematic maps, their most salient feature is the presentation of logical relationships (the structure of the network) in visual form. The findings from the literature on solving non-verbal intelligence test problems (such as Raven's progressive matrices, Raven, Raven, & Court, 1993) show that simple changes to the visual appearance of a problem, without changing the underlying logic, can have dramatic effects on item difficulty (Meo, Roberts, & Marucci, 2007; Primi, 2002; Vodegel Matzen, Van der Molen, & Dudink, 1994; Roberts,

Livermore, Welfare, & Theadom, 2000). Difficulty is affected not only by the *quantity* of rules and elements, but also by their *quality*, so that if the shapes used are particularly complex, difficult to name, or overlapped, then individual item elements and their relationships will be harder to identify, with a profound knock-on effect for identifying the underlying logic of an item (see Figure 1). It is hard for people to reason if they cannot identify what they are reasoning about. Hence, the *simplicity* and *coherence* criteria above can easily be mapped onto current research findings in intelligence.

\*\*\*\*\* INSERT FIGURE 1 ABOUT HERE \*\*\*\*\*

Deductive reasoning research has been very informative of the sorts of logical relationships that people find difficult to process (e.g., Evans, Newstead, & Byrne, 1993; Manktelow, 2012). This can have implications, for example, in understanding service patterns. The New York Subway is famously difficult to map, but the task of understanding the network is made harder because some services operate as *exclusive disjunctions*. For example, along the *Grand Concourse Line* in the Bronx, many stations are served *either by the B train, or the D train, but never by the B and D train together*. If services are difficult to comprehend, then the map will be likewise, irrespective of its configuration.

The provision of supplementary information on a map (e.g., concerning restrictions, exceptions, and opportunities for forward travel) is also of interest to reasoning researchers. Working memory capacity is challenged not only by the sheer quantity of such information that users are bombarded, but also by its *quality*, with much of this incomplete, ambiguous, or incongruent with expectations. For example, (taken from a London Underground map from 2008) if certain stations are flagged as having no late evening service, then it is a reasonable to expect unflagged stations to have no late restrictions, but this inference is valid only for the London Underground stations, not the London Overground stations on the same map (Roberts, 2008, 2012). The successors to Wason's (1972) incomprehensible social security claim forms, full of double-negatives, that led to his research into sentence-picture verification, are today's numerous ambiguous incomprehensible attempts to give people

assistance via poorly designed or inconsistently used information graphics. Better-intentioned, but no less pernicious.

### **The benefits of effective design**

What might be expected from a design that satisfies all of the framework criteria outlined above? A simple, coherent, balanced schematic map will have high *structural salience*, revealing the elements and their relatedness, and making the underlying network configuration easier to identify, facilitating both journey planning and learning, so that a virtuous circle is set up, with performance getting better as more is learnt. For such a design, we would expect fast journey planning, few errors, better remembered plans, and more easily reconstructed plans in the event of a failure to remember.

The design should also have good harmony, so that users like its appearance and accept it, and good topographicity, so that there will be no serious conflicts with users' mental models of the city, which might result in the map being rejected for lack of trustworthiness. Together, these will result in people electing to use the map rather than rely on asking for assistance or using computerised journey planners, also facilitating learning and boosting future performance.

In comparison, a poorly designed schematic will struggle to offer any of these benefits. A lack of simplicity and coherence can bury the underlying structure of the network. Such a map may even have little to offer compared with a topographical version, other than the simplification entailed in removing street details and most other landmarks. With gross neglect of the framework criteria (especially for poor harmony and topographicity), users will reject it outright and the design will be short-lived.

### **Conclusions: Back to Beck**

Henry Beck's work is often misunderstood. Many commentators herald him as the inventor of schematic maps, which is clearly not the case. Transport cartography and information design had been evolving in this direction long before Beck had even considered experimenting with this approach (Dow, 2005; Roberts, 2012). Beck's use of octolinearity is also often given too

much emphasis. Again, he is sometimes mistakenly asserted to have been the first to use this, and it is revered as a cartographic gold standard by many designers. We have already seen that this position is indefensible. The reality is that different networks have different topographical and geometric properties, and some may have poor compatibility with octolinearity (Roberts, 2012). Such misconceptions and preoccupations divert attention away from the possibility that some schematic maps might be more effective than others: Optimising the various criteria within a set of design rules is at least as important as the choice of design rules itself. Beck's real achievement is that he chose the design rules (octolinearity) and then, within this constraint, and with little precedent, produced an exceptional design: A textbook case of his adherence to the framework for effective design outlined earlier, and implying a better-than-usual lay-understanding of the cognitive psychology of the user. Figure 2 shows the topographical reality of the Paddington area (1), in comparison with Beck's first attempt at this configuration (2), and also what can go wrong if the framework is neglected. Hence, if Beck had used octolinear angles, but had not addressed the requirement for simplicity (3) – perhaps attempting to match topographical reality too closely – then a far less effective design would have resulted. Beck's early work was not special because it used straight lines, but because it had so few corners.

**\*\*\*\*\* INSERT FIGURE 2 ABOUT HERE \*\*\*\*\***

Of course, Beck could have chosen other angles for straightening the line trajectories (4), but the risk of poor coherence would have been considerable, for example with many non-parallel lines. However, even if he had attempted a non-octolinear design and maintained parallel lines, he could have chosen angles with poor harmony because of, for example, lack of perpendicular line crossings (5). Octolinear angles have a natural advantage in terms of this. Beck could have created an unbalanced design (6) or one with poor topographicity (7), in which the distortion conflicted too much with people's mental models of London. By avoiding this problem, users were more likely to appreciate the improved usability of the schematic map, and less likely to reject this new design for other reasons, hence ensuring the longevity of this approach for London and paving the way for this method of visual

communication to become widespread in the future. Today, it is easy to find schematic maps worldwide which fail to address adequately one or more of the five categories of criteria for effective design from the proposed framework. A better appreciation of Beck's early success, as well as the psychological factors that underpin effective design, should lead to this happening less often in the future.

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Figure 1. Four matrix items typical of the sort used in intelligence tests. Items 1 and 2 both have a rule that is straightforward to identify and apply, but Item 2 has more elements (six, as opposed to four for Item 1), making these harder to discern, and in turn the rule harder to identify. Item 2 should be the harder of the pair because of its higher cognitive load. Items 3 and 4 also have a straightforward rule, but the line trajectories in Item 4 are more complicated, making their relationships harder to identify, and therefore the rule harder to discover. Item 4 should be harder to solve than Item 3, despite being otherwise logically identical. Image © Maxwell J. Roberts, 2014. Reproduced with permission.

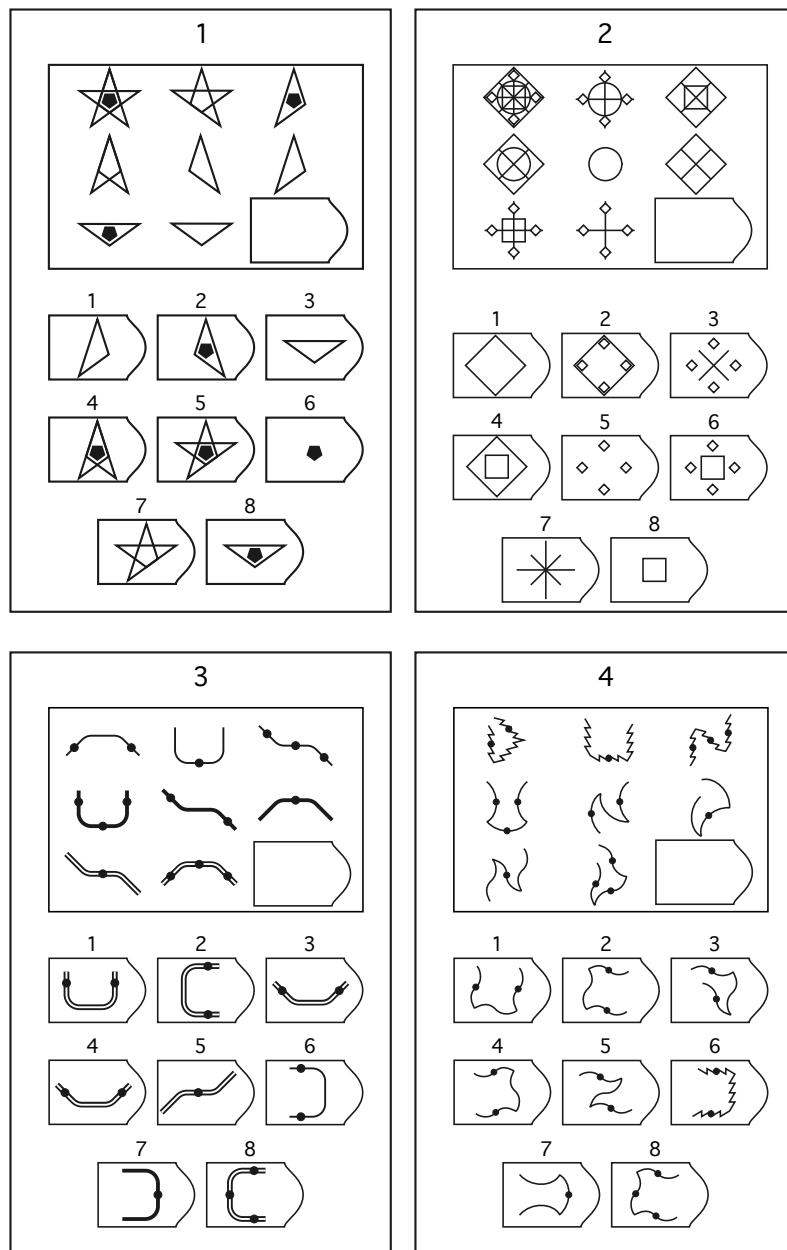
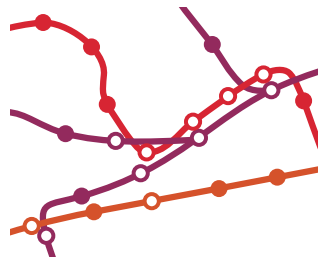


Figure 2. Sections of maps showing the line trajectories of an area of central London around Paddington. (1) represents topographical reality, as shown in maps immediately prior to Henry Beck. (2) shows Henry Beck's schematic depiction of reality. (3) demonstrates poor simplicity, with many corners, (4) has poor coherence, the trajectories are simple, but there are many different angles, and no pairs of lines are parallel. (5) has few angles and straight, parallel lines, but these do not cross at  $90^\circ$  and hence the harmony is poor. Such a design might be easy to use, but rejected by users. (6) has uneven station distribution and therefore poor balance, and (7) distorts topography considerably, hence *poor topographicity*. Image © Maxwell J. Roberts, 2014. Reproduced with permission.



1: geographical reality



2: Henry Beck's 1933 configuration



3: poor simplicity



4: poor coherence



5: poor harmony



6: poor balance



7: poor topographicity