Chapter 4
Peripheral Tangible Interaction

Darren Edge and Alan F. Blackwell

Abstract Much of our everyday interaction in the physical world is peripheral—many of the objects that reside on the periphery of our *awareness* also require or allow actions in the periphery of our *attention*, as we briefly touch, handle, move, or avoid them. When these objects are digitally augmented, computational operations extend beyond dedicated display screens and leverage our capacity for occasional and low-attention interactions in the physical world. The research presented in this chapter analyzes this phenomenon of peripheral tangible interaction. Understanding the use qualities of the resulting tangible notations is critical to the design of interfaces aiming to facilitate peripheral interaction. We discuss when and how to design for peripheral tangible interaction based on systematic analyses of user activities and of system qualities. We illustrate both through a case study: the design of ShuffleBoard, a tangible interface for desk work in an office context, in which interactive surfaces and digitally augmented physical tokens support interaction with significant tasks, documents, and people, alongside and concurrently with focal workstation tasks.

Keywords Peripheral interaction · Tangible interaction · Analytic design · Cognitive dimensions · Office work

4.1 Introduction

Much of our everyday interaction in the physical world is peripheral—many of the objects that reside on the periphery of our *awareness* also require or allow actions in the periphery of our *attention*, as we briefly touch, handle, move, or avoid them.

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S. Bakker et al. (eds.), *Peripheral Interaction*,
Human–Computer Interaction Series, DOI 10.1007/978-3-319-29523-7_4

When these objects are augmented to represent digital information, computation extends beyond attention-grabbing display screens, supporting occasional, and low-attention interactions in the physical world. We call this *peripheral tangible interaction*.

In this chapter, we discuss when and how to design for peripheral tangible interaction based on systematic analysis of user activities and system qualities. We illustrate both forms of analysis through a case study: the design of ShuffleBoard, a tangible interface for desk work in an office context. ShuffleBoard is not intended to be the primary focus of the user's attention, but is designed to be used alongside a conventional workstation.

Tangible interfaces have more conventionally been categorized as either "graspable media" on the one hand—located in the foreground of activity and at the focus of users' attention—or "ambient media" on the other, existing in the background of activity and at the periphery of users' attention (Ishii and Ullmer 1997). Both types of system draw on the agenda of "calm technology" that "engages both the center and periphery of our attention, and in fact moves back and forth between the two" (Weiser and Brown 1995). However, these two categories also reified the center and periphery of attention in fundamentally distinct media forms. In the development of ShuffleBoard, we needed a hybrid concept to describe the periodic, tangible interaction with peripheral, ambient representations—interaction that neither fully nor continuously occupies the center of the user's attention, nor remains on the periphery. We termed this "peripheral interaction" (Edge 2008), or "peripheral tangible interaction" (Edge and Blackwell 2009) to distinguish it from other, non-tangible user experiences.

Unlike transient input modalities such as gesture and speech, the persistence of tangible objects allows them to provide a notation representing system state as well as enabling control of underlying information. Tangible notations leverage both the material form of objects and their configuration in space. In terms of Norman's action cycle (Norman 1988), this unification of representation and control can help to bridge both the gulf of execution (since physical affordances can indicate the availability of digital actions) and the gulf of evaluation (since physical state can be tightly coupled to digital state). In other words, the use of tangibles has the potential to lower cognitive demands to an extent that might not be possible through non-tangible visual or audio interaction. To help designers fully exploit this potential, our goal is to provide guidance on both the identification of opportunities for peripheral tangible interaction and the design of tangible notations that encourage peripheral interaction in use.

In the remainder of this chapter, we first introduce our case study by describing the design of ShuffleBoard. We then describe several other peripheral interaction systems that will be used in design comparisons. We characterize peripheral interaction through a model of how different *workload profiles* can help or hinder its emergence. We then present an analytic design process for the design of tangible interfaces that have the specific goal of facilitating peripheral interaction, using the design of ShuffleBoard as a running example. Finally, we conclude with an outlook for peripheral tangible interaction, connecting the contemporary concept to a broad range of theories, technologies, and trends.

4.2 Design of a Tangible Interface for Peripheral Desk Work

The design of ShuffleBoard arose from an investigation into the potential for tangible interfaces to support desktop work in an office environment. Interviews with staff at a multinational technology company had uncovered a number of problems with existing work practices that could benefit from dedicated interaction support (see Edge 2008 for more).

A perceived problem associated with default email communication was that people no longer talked to one another as much—not only about particular issues, but general status. With only weekly project meetings, this had resulted in a general lack of awareness about the work status of other team members. Other problems related to the inaccuracy of time sheets; the inability to share information from physical note books, whiteboards, and sticky notes; and the inappropriateness of planning work in calendars that failed to reflect the informal reality of how work was carried out. In all cases, the problems appeared to stem from the interactional and attentional costs of creating and updating digital information structures *about* work, in parallel with actually *doing* it.

4.2.1 Interface Design

The core of the ShuffleBoard interface is a collection of poker-chip-sized *tokens,* laser cut from acrylic sheet, that represent items of common interest wit detailshin a work group: tasks, documents, and people (Fig. 4.1). Each token has a rotationally unique, circular pattern of holes. Interaction with these tokens takes place on a personal *interactive surface* located to one side of the user's keyboard, on the side opposite their mouse (i.e., near the non-dominant hand). We implemented this interactive surface using a tablet PC augmented with a webcam pointing down at the surface. The identity of each token is determined from the pattern of light from the screen shining through its identifying holes. When a token is added to the surface, the attributes of the corresponding digital object are rendered as a dynamic "halo" that follows any movement of that token around the surface. This visual approach offered a reasonably low-cost sensing solution at the time it was developed, although many alternatives are now available, including the use of capacitive sensing (Chan et al. 2012), optical sensing through glass fiber (Baudish et al. 2010), and magnetic-field sensing (Liang et al. 2014).

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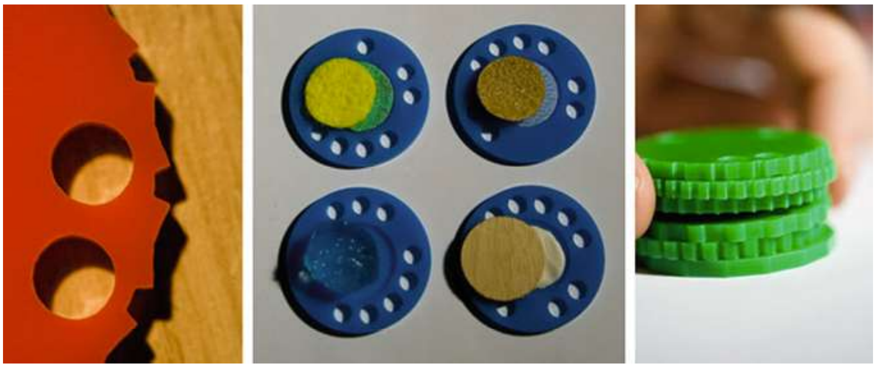

Fig. 4.1 Physical token design: (*left*) red task token with edge texture corresponding to the task owner; (*center*) blue document tokens with material attachments for identification; (*right*) green contact tokens with edge texture corresponding to other people in workgroup

A typical physical arrangement of tokens is shown in Fig. 4.2. Specific token attributes are selected by nudging the token in the direction of that attribute, in the position where it appears within the surrounding halo. Tokens support up to four controllable attributes corresponding to the four principal directions of the interactive surface, thus striking a balance between information content and ease of selection. The selected attribute can then be manipulated by turning or pressing a

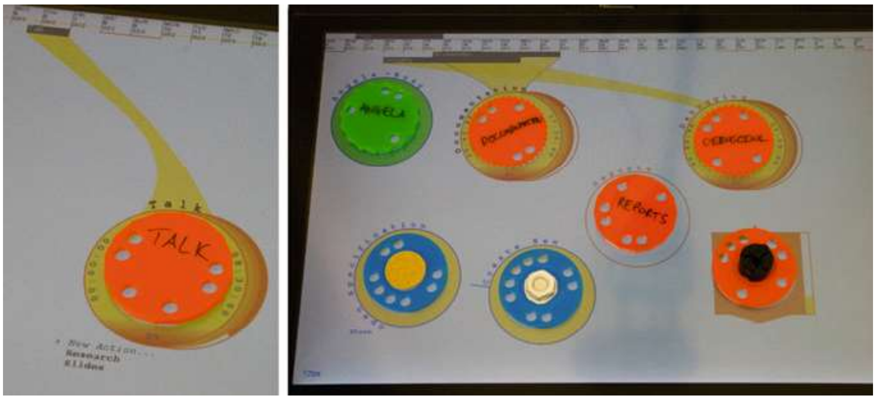

Fig. 4.2 Token halos on interactive surface. “Talk”: a task token showing its name and connection to the time line above, estimated time remaining to the right, work time completed to the left, and action items below. “Documentation” and “Debugging”: tasks overlapping in the time line. “Reports”: a task token with its halo minimized. “Angela”: a contact token showing a status of Busy and one task in the overlaid time line at the top of the screen. “Open Specification”: a document token identified by a disk of sandpaper linking to a collaborative document called Specification. “Create New”: an unbound document token. Unnamed red token with black Lego handle (*bottom right*): calendar tool

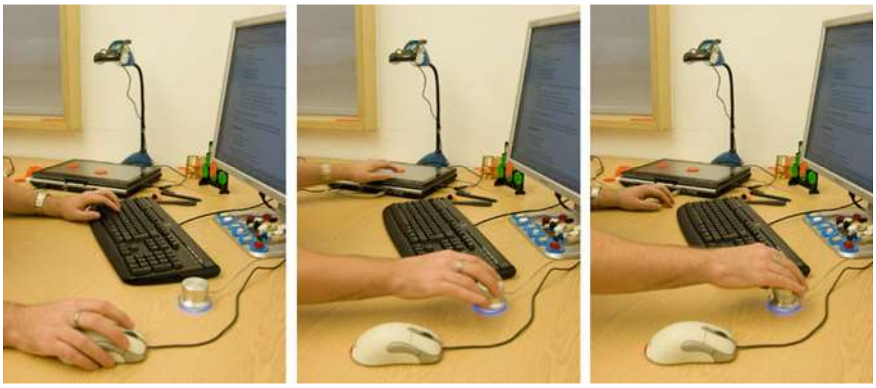

Fig. 4.3 Bimanual interaction design: (*left*) user working on the focal workstation PC, occasionally glancing at the interactive surface; (*center*) nudging a token in the direction of an attribute to change; (*right*) manipulating attribute with control knob

control knob (here, the Griffin Powermate) located on the other (dominant hand) side of the keyboard (Fig. 4.3).

The deliberate recruitment of both hands ensures that actions are intentional. Since we wanted to encourage casual touching without focused attention, it was important that unintentional actions should not require correction. An accidental knock to a token changes which attribute is selected, but does not change its value. This *bimanual safeguard* allows users to make rapid, intentional changes while also allowing tokens to be freely added, moved around, and removed from the interactive surface. Such use of bimanual interaction is supported by the prior experimental finding that given adequate visual feedback, the two hands can operate on distinct physical objects in disjoint physical spaces and still cooperate in the performance of a common task (Balakrishnan and Hinckley 1999).

All of the design elements introduced so far describe how we crafted each token as a *digital instrument*—a physical object that allows the creation, inspection, and modification of digital information (Edge 2008). Whereas conventional graphical interfaces require digital objects to either rest on the virtual desktop or be retrieved through transient menu and window structures, using tangible tokens as digital instruments allows such objects to be freely moved on, off, and around the surface. A screenshot of the ShuffleBoard surface displaying information “halos” around token positions is shown in Fig. 4.4.

The benefits of using tangible objects extend beyond their use as digital instruments. Our five-week field deployment of ShuffleBoard in a small technology company identified five further roles that tangible tokens can play in interface design. Tokens can act as a *knowledge handle*, helping users to remember, think about, and plan actions on its digital referent. Placing a token in a meaningful or memorable location, or arranging it with respect to other tokens, allows the token to act as a *spatial index* that leverages the structure of the physical environment. The physical form of a token allows it to act as a *material cue* for its visual detection and

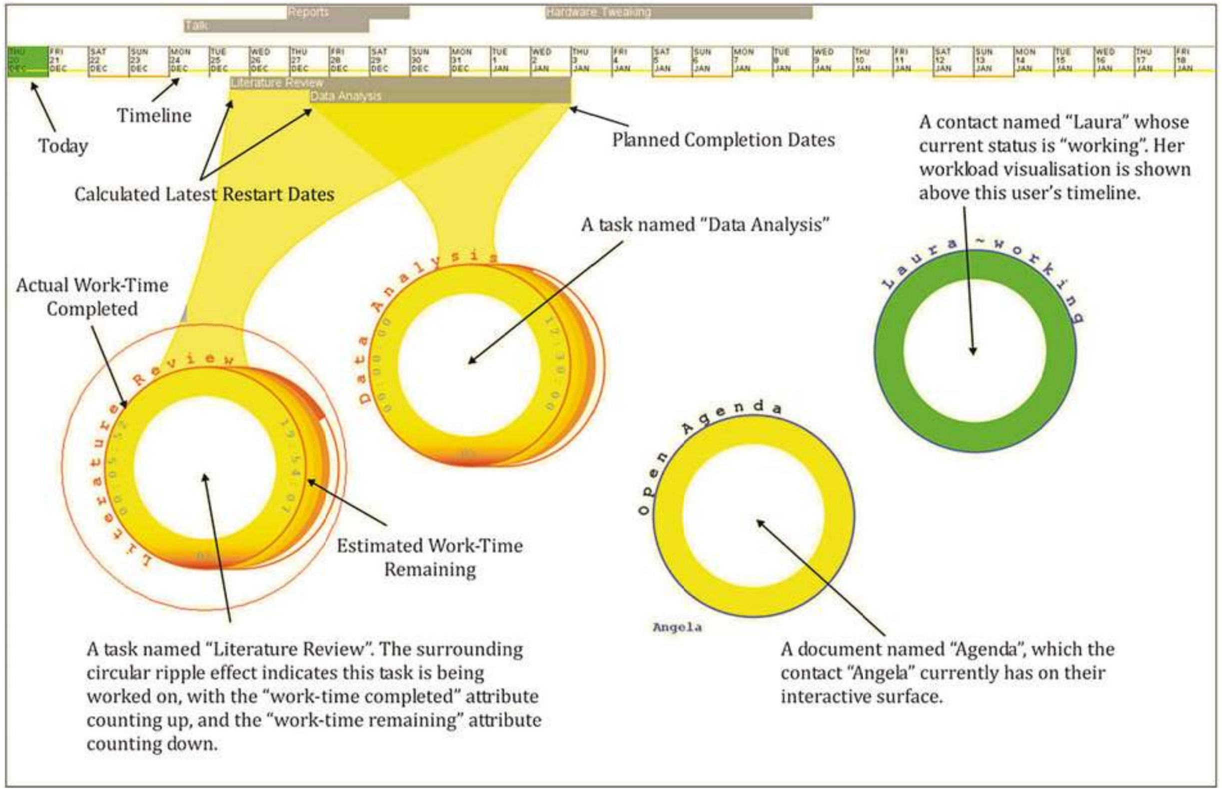

Fig. 4.4 Annotated screenshot of the tablet PC displaying information halos corresponding to tokens lying on its interactive surface. Specific visualization elements are described in detail in the following sections

identification. In social settings, the persistence of a token allows it to act as a *conversation prop* supporting deictic references to digital objects. Tokens can also act as a *social currency*, signifying roles, rights, and responsibilities through possession and exchange. Each of these qualities brings potential advantages over graphical user interfaces. The following sections describe how we designed the ShuffleBoard token types to support such interactions.

4.2.2 Task Tokens

Task tokens are cut from red acrylic in sets of 20 per user, with each set having a distinctive edge texture associated with the owner. The number of task tokens belonging to each user is deliberately constrained such that they become a scarce resource; owners need to decide which tasks are most important, recycling tokens accordingly. The physical transfer of task tokens acts as a proxy for delegation of tasks. These interactions are facilitated by the ability to annotate the surface with dry-erase markers.

Task management and time management are closely interrelated, and the digital representation of tasks is coupled with the digital representation of time—a calendar "time line" that forms the uppermost border of the interactive surface (Fig. 4.4, top).

The conceptual model underlying the digital representation of tasks is based on three user-controllable attributes: *planned completion date*, *estimated work time remaining*, and *action items*. Each can be selected by nudging the token in that direction, allowing modification by the control knob. *Latest restart date* and *work time completed* are derived from these primary attributes. Each task attribute is now described in turn.

Planned completion date is represented by the rightmost arc extending from the top of the task halo to the corresponding date on the time line.

Estimated work time remaining is represented numerically on the *right* of the halo by a time value, and graphically by a series of five overlapping, semicircular scales, corresponding to durations up to 1, 4, 10, 40, and 100 h, respectively. Each scale is broken down into 12 increments, allowing time estimates to be specified at a granularity commensurate with their probable accuracy: to the closest 5, 15, 30, 90 min, and 5 h, respectively.

Latest restart date is represented by the leftmost arc extending from the top of the task halo to the corresponding date on the time line. It is derived from the planned completion date, the estimated work time remaining, the scheduled working hours per day over the course of the task, and the number of overlapping tasks (under the assumption of an equal division of labor among tasks overlapping in time).

Action items are represented as a list of actions below the task token, accompanied by a "New Action…" control. Rotating the knob moves a cursor through the list, while pressing the knob allows the user to enter a new item or edit the selected item on the focal PC.

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Work time completed is represented on the left side of the task token halo, opposite the work time remaining. Nudging a task token then pressing the control knob toggles a timer that dynamically counts down from the estimated work time remaining. At most one token can be active at a time, and nudge-click on a different token will automatically transfer the timer to the new task. The currently active token is highlighted with an animated ring slowly pulsing around it.

4.2.3 Document Tokens

Document tokens are cut from blue acrylic and are plain disks, with no distinguishing edge textures. They are shared between all ShuffleBoard users, who can take them as desired from a single tray containing both document tokens and document-token materials. These materials are used for rapid recognition and identification of tokens in the physical environment and attach to tokens via circular recesses cut into the center of tokens' facing surfaces using Velcro.

Document tokens link to online collaborative editors, providing both identifiers and access control. Documents can be opened by placing the corresponding document token on an interactive surface and nudging it in any direction, followed by pressing the control knob. Placing an unlinked document token next to the token for an existing document activates a cloning mode in which clicking the control knob binds the new token to the existing document. There is no concept of document ownership, only of document-token possession. Anyone in possession of a document token may clone it and share access with anyone else.

Document tokens facilitate awareness among contacts by listing all users who are currently interacting with the document, or might do so. This lightweight form of social access control provides opportunities for ad hoc informal collaborations that are otherwise difficult to manage. It also creates opportunities for face-to-face interaction around the exchange of document tokens.

4.2.4 Contact Tokens

Contact tokens are cut from green acrylic and represent other members of the team or work group, existing primarily to support mutual awareness. Whereas document tokens provide a means of passively monitoring document interest, contact tokens allow the user to inspect and passively monitor the work status and work progress of other users. Each user has a contact token representing themselves, as well as tokens for each other ShuffleBoard user. The contact token representing a user has the same edge texture as the task tokens for that user.

When a contact token is placed on the interactive surface, the resulting digital "halo" displays the name and work status of the associated user. A user changes work status by nudging their own contact token upward and pressing the control knob.

When the contact token for another person is placed on the ShuffleBoard surface, the time line for that person is displayed above the user's own time line for comparison. This allows users to passively and peripherally monitor the work plans and progress of one another as they are updated in real time, which aims to address the reduced level of mutual awareness that can easily occur in the time between formal meetings.

4.2.5 Calendar Tool

Each user also has a special red token—a calendar tool—to interact with the time line. It can be used to adjust the expected number of available working hours, adjust the time line scale, and navigate the time line by scrolling with the control knob.

4.3 Related Work in Peripheral Interaction

In this section, we introduce systems and studies that have further demonstrated the potential for peripheral interaction since its initial conceptualization in the design and evaluation of the ShuffleBoard interface. In subsequent sections, we compare and contrast the associated system designs to the design of ShuffleBoard, focusing on their relative expression of use qualities that may help or hinder the emergence of peripheral interaction in practice. These comparisons also illustrate the generality of the presented use qualities themselves, through their application to systems targeting diverse user activities.

The CawClock (Bakker et al. 2012), NoteLet (Bakker et al. 2012), and FireFlies (Bakker et al. 2013) systems all aim to facilitate peripheral interaction in a primary school classroom context. The first system, CawClock, is an augmented analog clock visible to both teacher and children that allows partitioning of the clock face into discrete time sectors corresponding to the intended pacing of the current lesson. This partitioning is accomplished by arranging up to four tangible tokens, each with a different color and associated animal, around the perimeter of the clock face. As the minute hand passes through a particular sector, the system plays a soundscape based on the sound of the corresponding animal. The frequency of animal noises within a sector progressively increases until the minute hand leaves the sector. The tangible partitioning is sufficiently direct that the teacher can make adjustments through interaction on the periphery of her attention, while both teacher and children can benefit from peripheral aural awareness of lesson-time progression. The second system, NoteLet, combines a wearable wristband device and a camera located in the corner of the classroom. The teacher can make impromptu observations for later reference by either squeezing the wristband for a generic observation or by pressing a wristband button labeled with the name of a particular child being observed. The system responds by taking a time-stamped photograph that is also annotated with the child's name used to capture it (if any). The third system, FireFlies, is an open-ended tool for lightweight communication between teachers and children. It comprises a light object located on each child's desk, capable of illumination in each of four colors, a continuous animal-noise soundscape based on the distribution of colors, and a wearable teacher tool that allows the teacher to assign colors to children's light objects (e.g., to indicate a general status like independent work time, specific feedback like "you are working well," or commands like "come to see me"). FireFlies adds the notion of a peripheral light display to the concepts of a peripheral soundscape (from CawClock) and a peripheral, wearable control tool (from NoteLet). It is similar to ShuffleBoard in the respect that multiple tangible representations distributed throughout environment are controlled through a single control tool located ready to hand.

Another desktop target for peripheral interaction is the control of background music with minimal interruption to the user's primary activity on a focal PC. In an 8-week in situ deployment study (Hausen et al. 2013), four different modalities for peripheral music control were evaluated: using dedicated media keys on a physical keyboard, using a graspable knob supporting turn and press actions, using tap and stroke gestures on a touchpad, and using hover and wave gestures in front of a freehand gesture sensor. Dominant-hand interaction with a graspable knob, as used in the ShuffleBoard interface, was found to offer the greatest support for interaction on the periphery. In another study on alternative forms of peripheral music control (Probset et al. 2014), an interactive chair that interprets directional tilt gestures was shown to offer a shorter transition time back to the primary task after executing the desired command, at the expense of greater execution time, than directional swipe gestures on a dedicated tablet or the use of arrow keys on the existing keyboard (both of which require a hand to leave the position established by the primary task). Participants also welcomed the "promotion" of music control through dedicated tangible means, which resulted in increased engagement with that activity. This aligns with one of the findings from the evaluation of ShuffleBoard that tangibility has symbolic value in terms of communicating what is most important to users in their spatial and social contexts (Edge 2008).

Finally, a similar pair of contrasting approaches has also been developed for peripheral interaction with social media status indicators. In Do Not Disturb (Olivera et al. 2011), the user orients a regular polyhedron (e.g., a 12-sided dodecahedron) such that the uppermost face depicts their current "mood" from a fixed set of alternatives. In StaTube (Hausen et al. 2012), the user rotates an illuminated cylindrical knob to set a color-coded presence status (online, away, or do not disturb). This knob sits on top of a stack of illuminated disks indicating the presence status of selected social media contacts, supporting peripheral awareness as well as peripheral control of presence in a similar manner to contact token status messages in ShuffleBoard.

4.4 Defining Peripheral Interaction

We have previously defined peripheral interaction from several perspectives. Our most general definition emphasized that peripheral interaction could arise through each of two possible channels: the digital objects of interaction (i.e., the information tasks achieved through action) being peripheral to the user's primary activity, and the physical objects of interaction (i.e., the tangible means of representation and control) being peripheral to the user's primary location and orientation in space.

> Peripheral interaction can be seen as any kind of interaction with objects – physical or digital – that do not occupy the typical center of the user's attention. (Edge 2008, p. 20)

Our more specific definition in the context of the ShuffleBoard case study built on both of these aspects and further highlighted the role of task switching over time:

> Peripheral interaction is about *episodic engagement* with tangibles, in which users perform *fast, frequent interactions* with physical objects on the periphery of their workspace, to create, inspect and update digital information which otherwise resides on the periphery of their attention. (Edge 2008, p. 20, emphasis added)

Expanding on these definitions, we observe that peripheral interaction can arise from related interactions that are sufficiently low-intensity or low-volume so as not to occupy the user's center of attention. To put it another way, interaction can remain peripheral as long as the *workload* imposed by the interaction does not consume so many resources that it becomes the de facto focus of attention.

An established method for the subjective assessment of workload is the NASA Task Load Index or NASA-TLX (Hart and Staveland 1988). Although developed for the analysis of task performance, the six factors it uses to differentiate different sources of workload—temporal demand, mental demand, physical demand, effort, performance, and frustration—all play a role in determining the extent to which interaction can be performed on the periphery of attention.

The most significant component of workload for peripheral interaction is *temporal demand*. The original definition refers to the perceived time pressure due to "the rate or pace at which the tasks or task elements occurred," which can also be quantified by "comparing the time required for a series of subtasks to the time available" (Hart and Staveland 1988). Translating this concept to the domain of peripheral interaction, we can say that the *peripheral work volume* with respect to the user's focus (which may vary, or be unoccupied) is the proportion of time spent preparing for, performing, and recovering from peripheral interactions. Beyond some threshold in that work volume, interaction will always cease to be peripheral, instead becoming the main focus. However, a sufficiently high *peripheral work intensity* of the peripheral interactions themselves, arising from the other five non-temporal components of workload, may also demand the user's attention to the extent that those interactions become focal. In the general case, however, it is the combined contributions of both these components—the *peripheral workload*—that determines the resources remaining for *focal work* and the potential for interaction

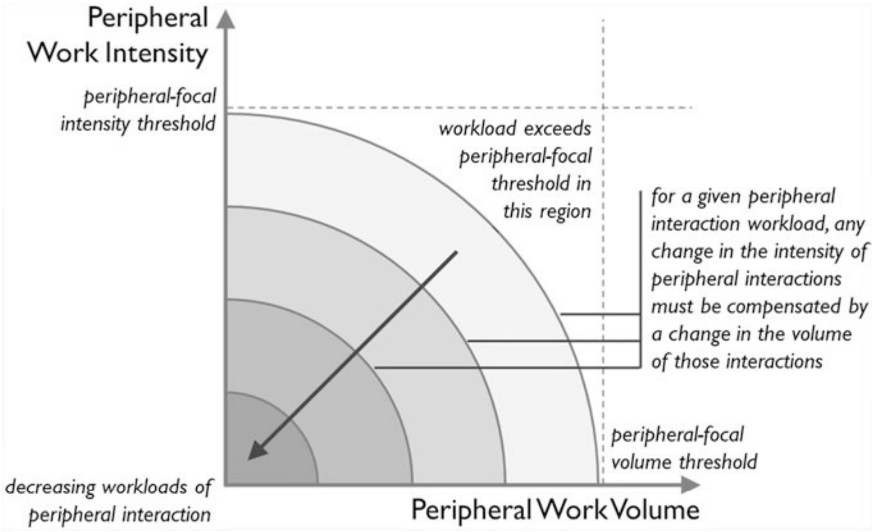

Fig. 4.5 How peripheral work intensity and peripheral work volume trade-off against one another for a given peripheral interaction workload. If interactions require too many resources or occupy too much time, they cease to be possible on the periphery of attention. *Curves* indicate that a balance between intensity and volume is more conducive to peripheral interaction than unbalanced combinations, since increases in either dimension have an additional, knock-on effect on the focus that can be achieve in the focal activity (Table 4.1)

on the periphery. These relationships are visualized in Fig. 4.5 and connected to the NASA-TLX components of workload in Table 4.1.

The value of this workload model is that it unifies the "attentional" and "temporal" definitions of peripheral interaction, in terms consistent with the attention investment framework for analysis of notation use (Blackwell 2002). During the design process, we can therefore describe how the abstract *use qualities* of an interface design combine to create a *workload profile* (expressed in terms of established NASA-TLX components) that determines the suitability of the interface for peripheral interaction. We give a detailed walkthrough of such a design process in the next section, using workload analysis to determine which use qualities best support peripheral interaction and illustrating each use quality with examples from the design of the ShuffleBoard interface and from other peripheral interaction systems.

4.5 Designing for Peripheral Tangible Interaction

We now present an analytic design process for the creation of interfaces aiming to facilitate peripheral tangible interaction. This process is a revised version of the process we have previously developed for the design of tangible interfaces in

Table 4.1 How NASA-TLX workload components affect peripheral interaction potential

Workload source	Workload component	Impact on peripheral interaction
Objective demands of the task	Temporal demand	Can increase *peripheral work volume* past the threshold at which interaction becomes focal and decrease the time available for *focal work*
	Mental demand	
	Physical demand	
Behavioral response to task	Effort	Can increase *peripheral work intensity* as well as induce and accumulate fatigue in ways that negatively impact *focal work* (equivalent to an increase in *peripheral work volume*)
	Performance (inverse scale)	
Psychological response to behavior	Frustration	Can increase *peripheral work intensity* and/or *peripheral work volume* if the user responds with greater attention and/or time in subsequent interactions, otherwise can negatively impact *focal work* by causing an ongoing distraction

general (Edge 2008; Edge and Blackwell 2009). It can be viewed as a rational, progressive refinement across three stages:

1. **Activity analysis** identifies user activities that could benefit from peripheral tangible interaction.
2. **Notation analysis** identifies the profile of use qualities that would facilitate or hinder peripheral tangible interaction with target activities.
3. **Interface design** generates candidate interface designs whose use qualities can be compared both to one another and to the target profile of use qualities.

The following sections elaborate on each of these stages, which together address the questions of *when* and *how* to design for peripheral tangible interaction.

4.5.1 Activity Analysis

Our design process begins with a consideration of which kinds of user activity might benefit from peripheral tangible interaction and the mechanisms by which it might help. We break this down by considering the potential for *Fluency* of peripheral interaction and how this might help lower the costs of activity switching, the different *Organizations* of activities and how they can create opportunities for peripheral interaction, the different *Rhythm*s associated with episodes of peripheral interaction and how they might suit different purposes, and the different *Meanings* assigned to the objects of peripheral interaction and how they arise from different kinds of activity. We describe this as analyzing the potential *FORM* of peripheral interaction in support of a target activity. By answering a series of probing questions associated with each of these concerns, the designer can develop a deeper understanding of whether peripheral interaction could support a range of candidate activities in a given context or for a particular purpose, as well as how such interaction might be realized in the form of concrete interface designs.

4.5.1.1 The Fluency of Peripheral Interaction

Peripheral interaction can lead to a perception of economy compared with achieving the same goals through sequential actions that need complete attentional focus. In the neuroeconomic model of attention investment (Blackwell 2002), this corresponds to reduced *cost* of notational action. Three major contributing factors for fluent interaction are economy of orientation, economy of action, and economy of transition. Considering how each could support a target activity will provide an initial indication of the potential for peripheral interaction.

Economy of Orientation *How could peripheral tangible interaction help users to orient their attention toward potential activity goals that may otherwise become neglected or forgotten as a result of interruptions, distractions, and overload?* For example, the tokens in the ShuffleBoard interface provide persistent physical reminders (tasks to do, documents to work on, and people to follow) that can be freely distributed throughout the user's workspace for coarse, spatial orientation. A similar effect is achieved through the physical distribution of light objects in the FireFlies interface (Bakker et al. 2013). In general, increasing the economy of orientation can reduce the mental demand, temporal demand, and effort of recalling and comparing possible goals before taking actions toward the chosen goal.

Economy of Action *How could peripheral tangible interaction help users to achieve goals in fewer, simpler, or faster actions, in ways that leverage multiple physical objects, multiple degrees of freedom of physical objects, or multiple dimensions of the physical world?* For example, in the ShuffleBoard interface, coarsely nudging a token toward the location of an attribute in its digital information halo simultaneously selects both the corresponding digital object and attribute of that object. Accurate control of the selected attribute is then delegated to the single control knob, which is operated in parallel by the other hand.[1] A similar streamlining tactic is used in the NoteLet system (Bakker et al. 2012), in which pressing a button corresponding to a child's name simultaneously takes a photograph and annotates it with a time stamp and the name of the child. In general, increasing the economy of action can reduce the physical demand, temporal demand, and effort of executing related action sequences following an activity transition.

[1]The interactive surface and control knob are positioned such that the non-dominant hand leads with coarse "nudge" operations, setting a frame of reference for the dominant hand to follow with accurate "turn" operations. This *asymmetric bimanual division of labor* follows the kinematic chain model of human bimanual skill (Guiard 1987) and allows interactions that are fast, accurate, and intentional.

Economy of Transition *How could peripheral tangible interaction help to minimize the costs of transitioning between the peripheral and focal activities, by digitally augmenting or reconfiguring the user, environment,*[2] *or activity?* For example, in the ShuffleBoard interface, the interaction elements can be acquired by pivoting slightly to one side.[3] Repeating this movement over time could help to develop the spatial and muscle memory that allows the transition to occur habitually and automatically, as occurs with mouse and keyboard. The interactive chair for peripheral music control (Probset et al. 2014) is motivated by a similar consideration of the user's relationship with the physical environment. In general, increasing the economy of transition can reduce the physical demand, temporal demand, and effort of repeatedly switching to and from the peripheral activity.

4.5.1.2 The Organization of Peripheral Interaction

Peripheral interaction can be configured in multiple ways with respect to the areas of separation and overlap between the focal and peripheral activities. Three prominent organizational forms are peripheral interaction with an embedded activity, a background activity, and a coupled activity. Considering how well a target activity could be supported by each of these forms will establish the focus against which interaction can be peripheral.

Embedded Activity *How could peripheral tangible interaction help the user to perform a neglected subactivity in parallel with its parent activity, in ways that allow timely processing of subactivity tasks resulting from the parent activity?* For example, the task tokens in the ShuffleBoard interface allow users to peripherally track the time spent on a task and update their estimate of the time remaining while actually working on that task on the focal workstation. Similarly, the FireFlies system (Bakker et al. 2013) is designed to support lightweight communication

[2]Reconfiguring the environment to create *entry points* for initiation and resumption of activities (Kirsh 2001) is known as *jigging* (Kirsh 1995). Strategies for arranging physical objects in the environment include arrangement by importance, function, frequency-of-use, and sequence-of-use (Sanders and McCormick 1987).

[3]Of the fundamental *kinematic pairs* (Reuleaux 1876) for the representation and control of 1D values—turning pairs (e.g., knob or joint), sliding pairs (e.g., slider or telescope), and twisting pairs (e.g., nut or bolt)—only the knob can be adapted as a stateless control of 1D values in an unlimited range (Edge and Blackwell 2006). Any other pair necessarily embodies a value (e.g., the angle of a joint or position of a slider). A knob is therefore superior for *temporal multiplexing* (Fitzmaurice 1996) in which the same control is bound to different representations over time. A mouse performs the same kind of control multiplexing in 2D, while the fixed key mappings of a keyboard and the fixed (until recycled) token mappings in the ShuffleBoard interface are examples of *spatial multiplexing* of control and representation, respectively.

about classwork while children are engaged in that work. In general, peripheral interaction with an embedded activity can reduce the mental demand of remembering to later switch to that activity and batch process the outstanding tasks, while also raising performance and lowering frustration compared with delayed serial processing.

Background Activity *How could peripheral tangible interaction help the user to perform a neglected activity in the background, independent of their current focus, in ways that encourage more frequent and habitual interactions?* For example, the contact tokens in the ShuffleBoard interface provide information about the status and activity of others. Developing the habit of adding contact tokens to the interactive surface and glancing at them periodically can help to increase mutual awareness within a team. StaTube (Hausen et al. 2012) operates on a similar principle. In general, prioritizing a background activity by creating the means for progress by peripheral interaction can reduce the mental demand of remembering to switch to that background activity (especially when there are no switching triggers in the user's focal activities) and increase the temporal demand of the background activity up to an acceptable level.

Coupled Activity *How could peripheral tangible interaction allow the coupling of activities as single hybrid activity, such that any time spent interacting for the purpose of one activity automatically makes progress in the other, coupled activity?* For example, in the ShuffleBoard interface, a side effect of using task tokens to manage the scheduling of individual tasks is that the user can immediately visualize the slack in their schedule after the overlap of tasks has been accounted for, i.e., time that can pass before the user must work full time on tasks in order to finish each task precisely on its deadline. Such "slack monitoring" is an important ongoing activity, but it no longer needs frequent user reflection after it has been offloaded to the "task management" interface. The CawClock (Bakker et al. 2012) similarly couples the activities of planning the pacing of a lesson and communicating that plan during the lesson itself. In general, coupling activities such that one or both may be performed on the periphery can reduce the temporal demand of scheduling independent activities and the mental demand of remembering to do so.

4.5.1.3 The Rhythm of Peripheral Interaction

The intervals between episodes of peripheral interaction can reflect the natural structure and flow of the target activity. Three significant rhythms are peripheral interactions at regular intervals, contracting intervals, and expanding intervals.

Regular Intervals *How could regular intervals between peripheral tangible interactions benefit user activities by helping to develop habits, maintain awareness, and support consistent progress?* For example, the interactive surface in the

ShuffleBoard interface provides a variety of information about tasks, documents, and people, with the goal of encouraging regular glances to maintain awareness of plans and progress even when the user is not in the process of actively updating token information. StaTube (Hausen et al. 2012) encourages similar regular glances to maintain awareness of contacts' presence status. In general, the more frequently the regular intervals occur, the greater the resulting temporal demand.

Contracting Intervals *How could contracting intervals between peripheral tangible interactions benefit user activities by helping users to track and manage their progress toward approaching times, dates, deadlines, or events?* For example, in the ShuffleBoard interface, interactions with task tokens are likely to increase in frequency as the task due date approaches. Our nonlinear scale for estimating the task work time remaining supports finer-grained estimates for shorter times remaining, encouraging more frequent interactions as tasks reach completion (e.g., to help others prepare for handover). Similarly, the density of animal noises in the CawClock soundscape (Bakker et al. 2012) increases as time runs out without a sector, encouraging more frequent time checks. In general, contracting intervals increase temporal demand for the target object, while across a collection of objects, the overall demand could remain relatively constant.

Expanding Intervals *How could expanding intervals between peripheral tangible interactions benefit user activities by following natural patterns of reinforcement, or reflecting a reduction in relevance over time?* For example, in the ShuffleBoard interface, a user may repeatedly interact with a document token as they author the document, but then interact with reduced frequency as the document stabilizes over time. On receiving a document token that links to an existing document, a user may also interact more frequently at the outset of the interaction when the content is unfamiliar, but then refer to it with reduced frequency over time as that content is reinforced through interaction. Similarly in FireFlies (Bakker et al. 2013), light–object interactions may follow expanding intervals with many early interactions as children encounter difficulties, followed by fewer and fewer interactions as children overcome those difficulties.

4.5.1.4 The Meaning of Peripheral Interaction

Peripheral interaction draws meaning from the activities it supports, and activities can demand support in a variety of areas. Three major sources of meaning are contributions to instrumental support, cognitive support, and communication support. Considering the extent to which each is required by the target activity will help to constrain the physical form and characteristics of the resulting notation.

Instrumental Support *How could tangibles facilitate peripheral interaction to create, inspect, or modify digital state in the context of the target activity?* For example, in ShuffleBoard, tokens provide privileged physical access to important digital tasks and documents, as well as dedicated physical control over their digital attributes. The tokens provide an instrumental advantage over conventional digital means of accessing and updating the same information. The interactive chair (Probset et al. 2014) provides a similar kind of privileged physical access to digital music control. In general, instrumental support is similar to economy of action in that it can reduce physical demand, temporal demand, and effort (although economy of action can apply to all interactions, not just instrumental ones).

Cognitive Support *How could tangibles facilitate peripheral interaction that creates and uses memory cues or other forms of external cognition*[4] *in the context of the target activity?* For example, in ShuffleBoard, tokens can be annotated, adorned with distinctive materials, and positioned in meaningful locations. Even though these physical actions have no direct effect on instrumental uses of tokens as ways of accessing and updating digital information, they make it easier for users to recall, think about, and make decisions about that information. The open-ended interpretation of light object colors in FireFlies (Bakker et al. 2013) provides a similar kind of support. In general, cognitive support is similar to economy of orientation in that it can reduce mental demand, temporal demand, and effort (although economy of orientation can also apply to instrumental actions).

Communication Support *How could tangibles facilitate peripheral interaction through their use as conversational props, communication channels, and representations of rights, responsibilities, and ownership?* For example, in ShuffleBoard, task tokens have edge textures representing the owner of that task. Provisionally assigning tasks to tokens in meetings allows people to take responsibility for completing different tasks. Receiving a task token from someone is a physical reminder to both complete the task and return the token, while receiving a document token represents the right to access the document. Finally, contact tokens provide a lightweight channel through which activity and status can be shared, like Do Not Disturb (Olivera et al. 2011). In general, communication support can improve the performance of teams meeting in the same space as well as the subsequent performance of individuals as a result of improved clarity and coordination.

4.5.2 Notation Analysis

The application of activity analysis results in a better understanding of how appropriate different forms of interface and interaction might be for supporting the activities of the target domain. The purpose of notation analysis—the next stage of

[4]The premise of *external cognition* is that cognition encompasses both internal representations "in the head" and external representations "in the world" (Scaife and Rogers 1996). It includes organizing physical objects to simplify choice, perception, or internal cognition, as well as using them to support epistemic actions that make mental computation easier, faster, or more reliable (Kirsh and Maglio 1994).

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the analytic design process for peripheral interaction—is to describe the abstract use qualities of interfaces in a manner that allows them to be compared, both against one another and against the requirements of the context in which they would be deployed. By viewing interfaces as notations, or abstract structures of representation and control, we can analyze the usability and suitability of those interfaces independently of their surface appearance and application semantics.

The original and best-known form of such abstract analysis is the Cognitive Dimensions of Notations framework, originally created by Green (1989), and since revised and updated by Green and Petre (1996) and Blackwell and Green (2003). Cognitive Dimension analysis has four main premises:

1. Usability is not an absolute, but a function of the activities to be performed, the notation on or through which those activities are performed, and the environment in which the notation is manipulated.
2. Usability is not a unitary scale, but a multidimensional space. Each dimension can be given a distinctive label, as is the case with the Cognitive Dimensions, with the aim of providing a shared vocabulary for design discussion.
3. Dimensions of usability trade off against one another, so attempting to increase the usability of a notation along one set of dimensions is likely to have the side effect of decreasing the usability of the notation along a different set of dimensions.
4. Design is the process of selecting design maneuvers whose associated trade-offs move the notation toward the desired dimensional profile of the activities to be supported.

The core of the framework is a list of Cognitive Dimensions (CDs), which describe abstract usability properties of notations. They are around 15 in number, although new dimensions are frequently being proposed and the set of dimensions is essentially open. The dimensions are generally neither beneficial nor harmful properties in themselves: Their contribution to overall usability depends on the activities to be performed. We denote CDs with typesetting convention of Cognitive Dimension$_{<\mathrm{CD}>}$. The application of CDs has been well documented in the CDs tutorial (Green and Blackwell 1998) and the CDs questionnaire (Blackwell and Green 2000). However, the analytic design of tangible interfaces is concerned not with purely digital notations, but with those that extend into the physical world. Rather than introducing new activities or dimensions to the CDs framework, we have previously identified particularly salient reinterpretations of the CDs that incorporated the characteristic features of physical media and the physical environment. We call these the Tangible Correlates of the Cognitive Dimensions (Edge and Blackwell 2006) and denote them as Tangible Correlate$_{<\mathrm{TC}>}$.

Both the Cognitive Dimensions and Tangible Correlates describe use qualities of notations that affect their suitability for peripheral interaction. We now introduce each cognitive dimension and its tangible correlate or correlates (where they exist), along with typical trade-offs between dimensions and the anticipated effects of each dimension on the components of interaction workload. Note that the purpose of this section is simply to introduce and illustrate the use qualities in a general sense. In any particular application of this process, designers should re-evaluate the significance of each dimension according to the specific demands and characteristics of the target activity and its activity context.

Consistency$_{<\mathrm{CD}>}$ Consistency describes the use quality that *similar semantics are expressed in similar syntactic forms.* For example, the digital tasks, documents, and contacts in ShuffleBoard share the same token form factor as they all represent objects of peripheral interaction, while the different colors of their respective tokens correspond to their different purposes. Higher levels of Consistency$_{<\mathrm{CD}>}$ can accelerate learning by reducing the initial mental demand, but it has little long-term impact on peripheral interaction.

Provisionality$_{<\mathrm{CD}>}$ Provisionality describes the use quality that *actions or marks can be reversed or removed.* For example, nudging tokens in ShuffleBoard makes provisional attribute selections with no lasting effects, unless they are followed by confirmatory manipulation actions with the independent control knob. Higher levels of Provisionality$_{<\mathrm{CD}>}$ support more casual and informal interaction by reducing the effort associated with making changes, at the cost of increased Viscosity$_{<\mathrm{CD}>}$ (since additional actions are required for confirmation or commitment). Lower levels have the potential to increase Premature Commitment$_{<\mathrm{CD}>}$ and Error Proneness$_{<\mathrm{CD}>}$.

Secondary Notation$_{<\mathrm{CD}>}$ Secondary Notation describes the use quality that *information can be expressed outside the formal syntax.* For example, tokens in ShuffleBoard can be annotated with dry-erase ink or augmented with material attachments in ways that aid the user's identification of tokens beyond the sensing capabilities of the system. Tokens can also be placed in meaningful or opportune locations in the physical environment (e.g., on a paper document, or hanging on a pin-board), away from their formal use on the interactive surface. Higher levels of Secondary Notation support informal extensions of the primary notation that can provide cognitive support and reduce mental demand, at the cost of increased Viscosity$_{<\mathrm{CD}>}$ (since additional actions are required to maintain the Secondary Notation when the primary notation is modified). Lower levels have the potential to exacerbate any problems with Role Expressiveness$_{<\mathrm{CD}>}$.

Progressive Evaluation$_{<\mathrm{CD}>}$ Progressive Evaluation describes the use quality that *progress-to-date can be checked at any time.* For example, the ShuffleBoard calendar shows the timings of scheduled tasks even when the associated task tokens are elsewhere. Higher levels of Progressive Evaluation$_{<\mathrm{CD}>}$ can reduce the mental demand of estimating or calculating progress, at the cost of greater Diffuseness $_{<\mathrm{CD}>}$ (since richer representations are necessary). Lower levels have the potential to increase Hard Mental Operations$_{<\mathrm{CD}>}$ as a result of needing to mentally track progress-to-date.

Premature Commitment$_{<\mathrm{CD}>}$ Premature Commitment describes the use quality that *the order of doing things is unnatural or overly constrained.* For example, the task tokens in ShuffleBoard support naming, time projection, due date setting, and action item setting in whichever order is most natural. Lower levels of Premature Commitment$_{<\mathrm{CD}>}$ can reduce mental demand and frustration, at the cost of introducing Hidden Dependencies$_{<\mathrm{CD}>}$ (since some attributes may depend on others in unanticipated ways). Higher levels have the potential to increase Viscosity$_{<\mathrm{CD}>}$ and reduce Closeness of Mapping$_{<\mathrm{CD}>}$.

Diffuseness$_{<\mathrm{CD}>}$ → Bulkiness$_{<\mathrm{TC}>}$ Diffuseness describes the use quality that *many lower-level marks are required to express higher-level concepts.* Its tangible correlate, Bulkiness, denotes the quality that *physical objects or representations occupy space in three dimensions*. For example, the ShuffleBoard tokens and interactive surface have a small desktop footprint in two dimensions (low Bulkiness$_{<\mathrm{TC}>}$) and the presence of one or two (in the case of document-token cloning) tokens on the surface is sufficient to enable all of the possible instrumental interactions with tokens (low Diffuseness$_{<\mathrm{CD}>}$). In another example, the limited size of the lower forearm and the wrist-worn nature of the NoteLet device (Bakker et al. 2012) means that it suffers more from the increased Bulkiness$_{<\mathrm{TC}>}$ of larger class sizes than the clip-on teacher tool of FireFlies (Bakker et al. 2013), which can freely grow with increasing child numbers. A minimum level of each dimension is required to reduce the effort associated with inspecting the current state. Higher levels have the potential to increase both Rigidity$_{<\mathrm{TC}>}$ and Rootedness$_{<\mathrm{TC}>}$.

Visibility$_{<\mathrm{CD}>}$ → Permanence$_{<\mathrm{TC}>}$ Visibility describes the use quality that *components can be viewed easily.* Its tangible correlate, Permanence, denotes the quality that *physical representations and control mapping can be preserved for future use*. For example, the ShuffleBoard tokens can be freely arranged beyond the confines of the interactive surface (high Visibility$_{<\mathrm{CD}>}$) and any one token can remain bound to its digital content for as long as desired (high representational Permanence$_{<\mathrm{TC}>}$). However, the binding between control knob and token attribute is transient (low control Permanence$_{<\mathrm{TC}>}$). A minimum level of each dimension is required to reduce the effort associated with recreating physical–digital mappings (if tangible objects are scarce) or physical representations of digital state (if physical space is scarce). Higher levels have the potential to increase the Bulkiness$_{<\mathrm{TC}>}$ of the interface as a whole.

Error Proneness$_{<\mathrm{CD}>}$ → Shakiness$_{<\mathrm{TC}>}$ Error Proneness describes the use quality that *the notation invites mistakes easily.* Its tangible correlate, Shakiness, denotes the quality that *physical representations are prone to accidental or irreversible damage*. For example, the physical size, texture, and weight of the ShuffleBoard tokens means that they are relatively stable on the interactive surface (low Shakiness$_{<\mathrm{TC}>}$), while the lack of spatial syntax[5] for token positions or

[5]Ullmer and Ishii (2001) define a tangible interface as one in which the physical configuration of objects partially embodies the digital state of the system. Conventional structural forms are *interactive surfaces* (where objects move on planer surfaces), *constructive assemblies* (where objects connect to objects), and *token+constraint systems* (where objects move within the constraints of other objects or non-planar surfaces). Each structural form also supports one or more types of spatial syntax: *spatial* interpretation of absolute object positions, *relational* interpretation of relative object positions, and *constructive* interpretation of object connections. While the ShuffleBoard interface has the structural form of an interactive surface, it does not have a spatial syntax for reasons of Viscosity$_{<\mathrm{CD}>}$ (explained later).

arrangements means that accidental movement of tokens has no effect other than to select token attributes (low Error Proneness$_{<\mathrm{CD}>}$). In another example, the relative ease of accidentally rolling the status-setting polyhedra in Do Not Disturb (Olivera et al. 2011) results in greater Shakiness$_{<\mathrm{TC}>}$ than the necessarily deliberate knob rotation in StaTube (Hausen et al. 2012). Lower levels of each dimension can reduce the frustration associated with dealing with errors and accidents at the potential cost of increased Viscosity$_{<\mathrm{CD}>}$, increased Rigidity$_{<\mathrm{TC}>}$, and reduced Structural Correspondence$_{<\mathrm{TC}>}$.

Juxtaposition$_{<\mathrm{CD}>}$ → Juxtamodality$_{<\mathrm{TC}>}$ Juxtaposition describes the use quality that *components can be viewed and compared side by side.* Its tangible correlate, Juxtamodality, denotes the quality that *multiple interaction modalities are coordinated across different physical spaces, objects, or senses*. For example, in ShuffleBoard, the attribute halos of multiple tokens can be viewed side by side on the interactive surface (high Juxtaposition$_{<\mathrm{CD}>}$), even while the value of the selected attribute is changing through eyes-free operation of the control knob in a separate physical space (high Juxtamodality$_{<\mathrm{TC}>}$ of the visual–tactile kind). In another example, the correspondence between the distribution of light objects and the resulting soundscape in FireFlies (Bakker et al. 2013) results in high Juxtamodality$_{<\mathrm{TC}>}$ of the audio–visual kind. The ideal level of Juxtaposition$_{<\mathrm{CD}>}$ is dependent on the target activity, and higher levels could raise the Bulkiness$_{<\mathrm{TC}>}$ of the interface (e.g., by requiring an increase in the size of the interactive surface). A minimum level of Juxtamodality$_{<\mathrm{TC}>}$ can help to reduce Shakiness$_{<\mathrm{TC}>}$ at the risk of increasing Hidden Augmentations$_{<\mathrm{TC}>}$ and Unwieldy Operations$_{<\mathrm{TC}>}$. The additional coordination required by higher levels has the potential to increase both mental and physical demand.

Viscosity$_{<\mathrm{CD}>}$ → Rigidity$_{<\mathrm{TC}>}$, Rootedness$_{<\mathrm{TC}>}$ Viscosity describes the use quality that *many lower-level actions are required to satisfy higher-level goals.* It has two distinct tangible correlates for different scales of interaction. Rigidity denotes the quality that *manipulation of objects or their arrangement is resisted.* Rootedness denotes the quality that *movement of objects or their arrangement is resisted.* For example, in the ShuffleBoard interface, the bimanual nudge-turn control scheme supports rapid attribute selection and manipulation (low Viscosity$_{<\mathrm{CD}>}$) with just the right amount of token sliding friction and knob rotational friction and inertia to ensure rapid yet accurate control (moderately low Rigidity$_{<\mathrm{TC}>}$). Tokens can be independently and freely moved between the interactive surface and physical desktop, as well as between the interactive surfaces of different contacts, e.g., for task delegation and document sharing (low Rootedness$_{<\mathrm{TC}>}$). In contrast, the interactive surfaces themselves are effectively confined to a single physical desktop location (high Rootedness$_{<\mathrm{TC}>}$). A minimum level of each dimension can help to reduce Shakiness$_{<\mathrm{TC}>}$, but higher levels are especially detrimental to peripheral interaction due to the additional physical demand, temporal demand, and effort required to modify information structures and manage their physical representations in space.[6]

Abstraction$_{<\mathrm{CD}>}$ → Automation$_{<\mathrm{TC}>}$, Adaptability$_{<\mathrm{TC}>}$ Abstraction describes the use quality that *the notation offers different types and levels of abstraction mechanisms.* It has two distinct tangible correlates for different targets of abstraction. Automation denotes the quality that *new behavior can be programmed and redefined.* Adaptability denotes the quality that *new states can be specified and redefined.* The creation and management of all such kinds of abstraction has sufficient mental demand that it requires focused attention and cannot generally be performed through peripheral interaction, although once created, they can be used in much the same way as the primary notation. The ShuffleBoard interface does not employ any Abstraction$_{<\mathrm{CD}>}$, either for the purpose of Automation$_{<\mathrm{TC}>}$ or Adaptability$_{<\mathrm{TC}>}$. Considering the abstraction potential of other interfaces, we can say that the use of a free-turning knob to set a user's status in StaTube (Hausen et al. 2012) has greater inherent Adaptability$_{<\mathrm{TC}>}$ than the use of polyhedra with a fixed number of faces in Do Not Disturb (Olivera et al. 2011), since knob rotation can cycle through an arbitrary number of states.

Role Expressiveness$_{<\mathrm{CD}>}$ → Purposeful Affordances$_{<\mathrm{TC}>}$ Role Expressiveness describes the use quality that *the purpose of each component is readily inferred.* Its tangible correlate, Purposeful Affordances,[7] denotes the quality that *possible physical acions have a clear and meaningful purpose.* For example, ShuffleBoard tokens are symbolic[8] representations of tasks, documents, and people (low Role

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[6]A fundamental trade-off between Rigidity$_{<\mathrm{TC}>}$ and Rootedness$_{<\mathrm{TC}>}$ exists when relations of association, dissociation, and order are expressed through the relative arrangement of physical objects in space. Engelhardt (2002) presents the six fundamental forms of spatial syntactic relation: spatial clustering; separation by a separator; lineup; linking by a connector; containment by a container; and superimposition (stacking). The relations of stacking, connection, and containment are based on physical bonding through gravity, linkage, and common enclosure, respectively, making them easier to move and relocate as a unit, but more difficult to reconfigure due to the requisite breaking and making of such bonds (high Rigidity$_{<\mathrm{TC}>}$, low Rootedness$_{<\mathrm{TC}>}$). In contrast, the relations of lineup, clustering, and separation are all based on perceptual arrangement, making them easier to reconfigure but more difficult to move and relocate as a unit (low Rigidity$_{<\mathrm{TC}>}$, high Rootedness$_{<\mathrm{TC}>}$). Since the auxiliary work activities in the case study would benefit from both low Rigidity$_{<\mathrm{TC}>}$ and low Rootedness$_{<\mathrm{TC}>}$, we developed an alternative, bimanual control mechanism based on Juxtamodality$_{<\mathrm{TC}>}$ that avoided the need for a spatial syntax.

[7]The concept of *affordance* developed by Gibson (1979) refers to the opportunities for action arising from the relationship between an animal and its environment. In its introduction to the HCI community, Norman (1988) describes affordances as messages conveyed by objects "about their possible uses, actions, and functions." Purposeful Affordances$_{<\mathrm{TC}>}$ are thus the use quality that messages conveyed by objects relate directly to their intended opportunities for interaction.

[8]The science of semiotics studies how something can stand for something else. In the semiotics of Peirce (1931–1958), *iconic* signs are those based on literal, analogical, or metaphorical similarity, while *symbolic* signs are those based on arbitrary or conventional rules or laws. Although iconic signs have greater Role Expressiveness$_{<\mathrm{CD}>}$, they also have greater Bulkiness$_{<\mathrm{TC}>}$ and lower Adaptability$_{<\mathrm{TC}>}$.

Expressiveness$_{<CD>}$). Some initial instruction is required for users to learn these mappings, but once past this initial learning curve (as with low Consistency$_{<CD>}$), there is relatively little impact on the potential for peripheral interaction. While the physical form of the ShuffleBoard tokens is not a literal representation of the underlying information objects, the material affordances of the poker-chip-like form factor allow the tokens to be annotated with dry-erase ink, picked up, placed on, and slid across the interactive surface, and so on (high Purposeful Affordances$_{<TC>}$). In another example, the use of a free-turning knob to set the symbolic color of a user's status in StaTube (Hausen et al. 2012) has lower Role Expressiveness$_{<CD>}$ and lower Purposeful Affordances$_{<TC>}$ than the use of polyhedra with a fixed number of iconic "mood" faces in Do Not Disturb (Olivera et al. 2011). High levels of Purposeful Affordances$_{<TC>}$ provide an ongoing benefit in terms of physical demand, at the cost of a potential reduction in future Adaptability$_{<TC>}$.

Hidden Dependencies$_{<CD>}$ → Hidden Augmentations$_{<TC>}$ Hidden Dependencies describes the use quality that *important links between components are not visible*. Its tangible correlate, Hidden Augmentations, denotes the quality that *physical objects are digitally augmented in a non-obvious manner*. For example, the calendar visualization in ShuffleBoard makes the dependencies between task time estimates, task due dates, and overlapping tasks explicit through the concept of "latest restart date" (low Hidden Dependencies$_{<CD>}$). While the position of the camera pointing at the interactive surface and the hole-based identification patterns cut into each token is a clear indication of the sensing mechanism, the bimanual control mechanism is not obvious (moderate Hidden Augmentations$_{<TC>}$) and must be learned. Although Hidden Dependencies$_{<CD>}$ could have a lasting effect on mental demand, Hidden Augmentations$_{<TC>}$ typically affects only the initial learning process.

Hard Mental Operations$_{<CD>}$ → Unwieldy Operations$_{<TC>}$ Hard Mental Operations describes the use quality that *the notation places a high demand on cognitive resources*. Its tangible correlate, Unwieldy Operations, denotes the quality that *the notation places a high demand on physical resources because of the nature of objects (e.g., size, shape, structure, or weight) and the actions required on them*. For example, in the ShuffleBoard interface, the ability to visually scan the desktop environment for physical tokens reduces the mental demand of recalling and holding in mind a wide range of potential interaction targets (low Hard Mental Operations$_{<CD>}$). The coordination requirements of the bimanual nudge-turn control scheme exhibits the minimum level of difficulty (mild Unwieldy Operations$_{<TC>}$) to avoid Shakiness$_{<TC>}$, although in general higher levels of Unwieldy Operations$_{<TC>}$ have a direct and undesirable impact on physical demand. The use of an interactive chair for peripheral music control (Probset et al. 2014) could easily elevate Unwieldy Operations$_{<TC>}$ to a high level.

Closeness of Mapping$_{<CD>}$ → Structural Correspondence$_{<TC>}$ Closeness of Mapping describes the use quality that *the representation closely resembles the* *domain.* Its tangible correlate, Structural Correspondence, denotes the quality that *the physical notation matches the structure of the underlying digital representation.*[9] For example, in the ShuffleBoard interface, the halo visualization of task token attributes is a direct representation of their values (high Closeness of Mapping$_{\langle \text{CD} \rangle}$), while the single degree of freedom of the knob corresponds directly to the single dimension of those values and visually moves them in the same direction (high Structural Correspondence$_{\langle \text{TC} \rangle}$). While low Closeness of Mapping$_{\langle \text{CD} \rangle}$ might increase the mental demand of initial learning, low Structural Correspondence$_{\langle \text{TC} \rangle}$ could have long-term effects on mental demand and frustration.

4.5.3 Interface Design

The third and final step of the analytic design process for peripheral tangible interaction is *interface design*. In this step, the designer generates interface design concepts inspired by the probing questions of the first step in the process, *activity analysis.* The prospective use qualities of these design concepts can then be analyzed and compared to the target profile of use qualities generated by the second step in the process, *notation analysis*. The purpose of these comparisons is to identify areas for improvement and to provide rationale for the design changes that aim to make such improvements. Since the use qualities of notations are holistic in nature, design changes have the potential to affect several use qualities simultaneously. Following a design change, all use qualities of the new notation should therefore be re-evaluated to check for unintended or unexpected side effects. When these side effects are negative, the designer must weigh up the resulting trade-off between the two design options. The abstract nature of use qualities means that the same analysis of trade-offs can be applied to the comparison of *any* competing designs, even if they embody fundamentally different notations.

In the design of ShuffleBoard, our application of activity analysis helped us to identify that in the desk-based, office context, the management of auxiliary work activities was a candidate for peripheral tangible interaction. It also suggested the basic idea of using physical tokens to represent items of shared interest within work groups: tasks, documents, and people. However, the final form of the interface, especially its separation of representation (tokens) and control (knob) as a way to facilitate bimanual interaction, was driven by notation analysis that highlighted problems with the use of spatial syntax for that particular activity context. Our

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[9] In the instrumental interaction framework (Beaudouin-Lafon 2000), the match between physical degrees of freedom and digital dimensions of control is called *integration* and the similarity between physical actions and digital effects is called *compatibility*. Structural Correspondence$_{\langle \text{TC} \rangle}$ combines these two properties and extends to the representational as well as control aspects of a notation. The third component of the instrumental interaction framework, *indirection*, refers to the spatial offsets between input and output that are created through Juxtamodality$_{\langle \text{TC} \rangle}$.

analytic framework is sufficiently general that it has the potential to create similar insights into any form of interface that bridges the physical and the digital—not just tangible interfaces, but all kinds of mobile, wearable, and ubiquitous interfaces that aim to facilitate interaction on the periphery of the user's attention. We discuss this broader context of applicability in the following and final section.

4.6 Outlook for Peripheral Tangible Interaction

This chapter has described analytic and design considerations for peripheral interaction through detailed consideration of a specific case study, the ShuffleBoard system for peripheral task management. ShuffleBoard was an early example of a fully functional peripheral tangible interface, which at the time of development was nearly unique for being deployed for evaluation of usage in context ("in the wild") during routine professional activity.

Previous studies of tangible interaction in professional contexts at that time had mainly focused on existing tangible representations: These might subsequently have been augmented for interaction with digital systems, or even used alongside such systems without specific design interventions (e.g., MacKay 1999). The ShuffleBoard interface was a completely novel system design, featuring tangible interaction that was created in response to a specific set of contextual requirements. As a result, ShuffleBoard provided an opportunity to study explicit design rationale in far greater detail and to apply the resulting observations as a basis for future design of novel peripheral tangible interaction systems intended to be deployed in the wild.

Although the specific sensing and fabrication techniques used to implement ShuffleBoard employed the hardware capabilities of that time (laser cutting, pen-sensing tablets, rotary controllers, template-based machine vision), the analytic design process that we have presented in this chapter is wholly appropriate to more recent generations of interactive devices. The market drivers for these devices continue to reflect Weiser's manifesto for ubiquitous computing, and to support the "calm" interaction style that he hoped would replace intrusive digital technologies (Weiser and Brown 1995). However, it has become clear that Weiser's somewhat utopian vision has not yet been realized in user experiences of contemporary technology. While many would prefer that technology receded into the background as Weiser hoped, the reality of contemporary technology products is that they are even more foregrounded than when Weiser advocated calm computing. Personal mobile computing devices such as tablets and cell phones, rather than moving technology to the periphery of our attention, have placed it ever more constantly at the center, resulting in the familiar complaints that social structures and even physical infrastructure are being degraded by inappropriate focus on mobile devices rather than (say) spoken conversation or attending to vehicle control.

This current situation gives particular urgency to a more sophisticated understanding of the relationship between focus and periphery, just as Weiser himself hoped would be achieved. Our FORM framework for analysis of peripheral interaction in support of a target activity is a timely contribution to this understanding. When combined with notation analysis, it supports an analytic design process for the design of peripheral tangible interaction devices that fit within a wide range of task contexts.

The commercial opportunities associated with those contexts are now clear, especially in the growing markets for wearable devices, and for “Internet of Things” products. However, at the time of writing, many of the interaction design approaches developed for such products seem to have retained the old emphasis on capturing and holding the user’s attention, whether through portable touch screens that can only be operated while looking at them, head-up displays that are superimposed on the user’s visual field, gaze tracking that explicitly monitors the user’s level of focus, or even immersive virtual reality headsets that prevent the user from employing peripheral attention.

This situation is not sustainable. It is clear that the number of CPUs in proportion to the number of people on Earth is a ratio growing so rapidly that it is inconceivable for us to continue giving focal attention to the user interface. If focal attention is not possible, peripheral interaction must be the central paradigm of the future.

Furthermore, computation is becoming embedded in the physical fabric of our material environment in increasingly diverse ways. Beyond the laser-cutting technique that we used to fabricate the ShuffleBoard tokens, other rapid fabrication methods such as 3D printing are combining with the popular culture of making and hackerspaces to result in a dramatic flowering of novel forms for digital devices. Before long, these will not simply imitate existing objects (such as phones, watches, or glasses), but will open up completely novel product categories. Similarly, the embedded computation of IoT products will mean that familiar household objects will become tangible interfaces, whether or not their shapes are explicitly modified.

Ultimately, humans are embodied beings who will interact with digital infrastructure through embodied actions and embedded physical forms. These forms will necessarily carry representational, control, and notational functions of the kinds that we have discussed in this chapter. It will become increasingly necessary to understand interactions of such products in relation to our own evolved physical capabilities (such as bimanual action and cross-modal sensing). The framework for peripheral tangible interaction that we have presented in this chapter is a comprehensive response to this urgent need.

Acknowledgments This chapter is based on research funded by The Boeing Company and conducted as part of a Ph.D. at the University of Cambridge Computer Laboratory, available as a Technical Report at http://www.cl.cam.ac.uk/techreports/UCAM-CL-TR-733.html.

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