Design Space of Programming Tools on Mobile Touchscreen Devices

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ABSTRACT
While mobile touchscreen devices are ubiquitous and present opportunities for novel applications, they have seen little adoption as tools for computer programming. In this literature survey, we bring together the diverse research work on programming-related tasks supported by mobile touchscreen devices to explore the design space for applying them to programming situations. We used the Grounded theory approach to identify themes and classify previous work. We present these themes and how each paper contributes to the theme, and we outline the remaining challenges in and opportunities for using mobile touchscreen devices in programming applications.

Author Keywords
Programming; touchscreen; source code; IDE; smartphones; tablets; software development;

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces; D.1 Programming Techniques; D.2.6 Software Engineering: Programming Environments

INTRODUCTION
Mobile touchscreen devices are now widely used throughout society. Not only do they enable new applications and bring computing to new venues, but they are also increasingly replacing or being used in combination with desktop PCs and laptops for many applications. However, one area that has been relatively slow in adapting to these devices is software development. This is understandable considering the drawbacks of mobile devices. The absence of a physical keyboard, small screen space and limited processing capabilities are some of the barriers preventing them from becoming usable platforms for programming [1, 49, 51].

Traditional programming environments or Integrated Development Environments (IDEs) used on desktop PCs and laptops typically have been designed for use with a mouse and a physical keyboard [49]. Porting these environments as they are to mobile devices would be impractical and result in many usability issues [8, 49]. Hence designing for mobile devices requires keeping in mind their drawbacks and interaction style. This raises questions regarding how and what kinds of usable software development can be enabled on mobile devices by leveraging their unique capabilities and in what contexts can they be useful.

Although it is unlikely that professional developers will use mobile devices as primary programming devices, enabling usable programming on mobile devices can potentially benefit students in educational settings, end-user programmers, and collaborative teams, just to name a few. Mobile devices are being considered for use in classrooms for computer science programming courses; therefore, making programming environments usable on these devices could benefit these efforts [27, 59]. Additionally, many visual programming languages and languages for novice programmers can be implemented on mobile touch devices, making them accessible to beginners of all ages [28, 38].

Mobile devices can also be used as peripheral devices in professional programming environments to facilitate certain programming tasks [9, 45]. Programming can also be a collaborative process and using mobile devices such as phones and tablets in combination with desktops or even by themselves can promote collaborative and co-located programming tasks such as code review, problem solving and pair programming [9, 36, 45]. They can also give programmers a sense of uninterrupted programming when they are in transit or are away from their desktop PCs [17]. Another important strength of mobile devices is that they enable multimodal input such as speech, pen, and image input. Pen input, in particular, can be incorporated in the above mentioned scenarios [36, 45].

Although we can see that the notion of enabling usable programming on mobile devices is interesting and potentially useful, the relatively slow and rather skeptical adoption of these devices for programming so far tells us that it is also nontrivial. While previous work done in this area is somewhat varied and provides different perspectives on the topic, we should keep in mind that this is a problem with a number of variables and numerous possibilities and that each of the previous articles has focused on one particular facet of the problem and has designed, for example, for a particular device type, context, and set of programming tasks.

Our goal in writing this survey article is to coalesce the research work done so far in reference to using mobile touchscreen devices for programming purposes to identify the design space and challenges in bringing programming tasks to them. Given the variety in the past work, we aim to provide a coherent review by categorizing related work under themes. We hope to provide a clear big picture as well as some useful low-level details covered in existing work and make apparent the possibilities explorable on these devices for programming. This article will be useful to anyone who is doing research in related areas or intends to use these devices for programming or develop software to support programming on them.
Scope of the Survey
For the purposes of this survey, we only include mobile devices with touchscreens enabling direct touch and/or pen input. We mainly cover programming support enabled on smartphones and tablets. However, we also discuss the programming functionality designed for tablet PCs or laptops with touchscreen displays only if the functionality could also be used exclusively on tablets as well without requiring the use of a physical keyboard. We do not discuss the work done on the interactive tablet devices of the 60s and 70s [2, 14] in order to keep the focus on more recent work and the significantly evolved tablet devices of today.

We include papers that discuss the use of mobile devices, either as primary devices or in combination with desktops or other devices, to enable some aspect of programming. We do not include work done on the broader non-programming tasks involved in software development.

The articles surveyed are summarized in Table 1. There are a total of 23 articles that have been published between 2006 and 2016 with the bulk of them (20/23) published between 2010 and 2015. Most of the articles have been published at ACM or IEEE conferences on HCI and/or software engineering. Our search terms included "programming + phone", "programming + touchscreen", "source code + touchscreen", "programming + tablet", and "software development + touchscreen". We found other articles using forward and backward citation tracking.

Taxonomy
The key research questions answered by the survey are as follows:

- What are the main themes in which the ideas or implementations presented in the papers can be categorized based on their primary focus and contributions?

- In each of the above themes, what kinds of programming functionality have been enabled or addressed on the mobile touchscreen devices?

- In what ways have the papers leveraged the interaction style and features of mobile touchscreen devices to enable or address the above programming functionality?

- How have the implementations been received by users?

We used the Grounded theory approach to literature review [63] to identify the themes. We present the main themes identified in the papers in the following sections and in each section, discuss the papers belonging to the corresponding theme with respect to the remaining research questions before concluding with a discussion. A paper discussed under a theme may contain aspects pertaining to a different theme and in such cases, we briefly mention those aspects of the paper in the latter theme. It should be noted that many of the papers discussed in this survey present design sketches or prototypes and don’t include evaluation studies. A summary of the survey is presented in Table 1.

THEME 1: FOR SMARTPHONES, ON SMARTPHONES
In this section, we discuss work that involves support for developing applications (apps for short) on mobile phones which can also be deployed on the phones. While TouchDevelop [58] and Mobidev [51] implement complete environments for developing apps, GROPG [42] presents a complementary feature enabling debugging of mobile apps using only smartphones.

Novel programming language with features amenable to smartphone interaction
TouchDevelop is a new programming environment tailor-made for developing and deploying mobile apps using only smartphones and by using the content, sensors and features present on the phones [58]. Although classrooms are perceived as the main context for TouchDevelop’s intended use [59, 60], later studies show that it is largely used by end-users who are mostly inexperienced programmers [3, 35].

Although some of TouchDevelop’s features were designed specifically to promote ease of use on phones, such as being statically typed to enable autocompletion, and with deliberate limitations, such as no support for user-defined types, it is still designed to contain many features common to imperative, object-oriented, and functional programming languages [58]. This helps users transfer their skills from these paradigms to TouchDevelop. The environment is also designed for use on a cloud-connected device to enable sharing of scripts.

The UI elements, consisting of code blocks, menu options and custom keypads, are designed to be easily selectable using finger taps. Programming using TouchDevelop requires the use of the regular on-screen keyboard only to enter a string literal or to rename a variable.

A study involving the analysis of 209 TouchDevelop scripts [3] found that about one third of the scripts had no functional purpose and had a low code reuse ratio (5%) [3]. A large-scale longitudinal study involving 17,322 TouchDevelop scripts and 4,275 end-users [35] found that there was high code reuse ratio (58%) and additionally, that most of the scripts were small in size [35]. Most users were novices and were active initially but later left or became less active [35].

Use of a graphical editor and camera feature to facilitate app-development
Motivated by the widespread availability of smartphones in emerging countries where desktops and laptops are relatively less accessible, Seifert et al. present Mobidev which is a development environment built for creating web-based mobile apps using only smartphones [51]. Hence, enabling the creation of apps with basic GUI elements on smartphones could potentially benefit many kinds of users including programmers, students, and end-users in many contexts including classrooms and workplaces.

Mobidev is a hybrid environment combining visual and text-based programming. The UI of the apps can be created by either using a graphical editor called the UIBuilder or by scanning a UI sketch of the app using SketchBuilder [51]. The UI
elements or widgets supported include text fields, drop-down boxes, buttons, radio buttons and checkboxes.

UIBuilder employs touch gestures to select widgets from menus and place them on the screen using drag-and-drop. SketchBuilder uses a camera image of a paper UI sketch as input and performs some basic image processing to identify the UI elements and workflow. The recognized UI elements can then be edited with the UIBuilder.

The evaluation of the UIBuilder and SketchBuilder of the Mobidev environment found that users spent a significant amount of time typing the back-end of the apps. Users spent more time drawing sketches and using the SketchBuilder than the UIBuilder and in general, preferred using the SketchBuilder stating that it was “fun” to work with.

**Code folding and transparent overlays for compact representation**

Traditionally, debugging of mobile phone apps is either done by running a desktop debugging application on an emulator, or by connecting a mobile device to a desktop or laptop computer. GROPG (GRaphical On-Phone debuGger) is a graphical debugging tool that provides the features of desktop debuggers on Android phones [42].

GROPG provides features such as viewing the debuggee’s source code in context, setting and editing breakpoints, inspecting and changing the debuggee’s memory values, viewing current threads and runtime stacks, and a user interface providing simultaneous views of the debuggee and debugger.

In order to provide the debugging features that are available on desktop applications on space-constrained smartphones, GROPG implements a graphical and interactive user interface with expandable fields i.e. code folding, and a transparency-adjustable debugger pane on top of the debuggee application to free the users from switching screens to interact with the debuggee and debugger [42]. The user interface is accessed using tap and multitouch.

In a preliminary study, GROPG was compared with Android’s DroidDebugger\(^1\) which has a heavy text-based interface and lacks the graphical, interactive UI of GROPG. Users took less time and fewer number of steps to perform the debugging tasks using GROPG.

**Discussion**

Studies have shown that one of the main challenges that mobile app developers face is the complexity involved in testing their apps due to emulators lacking necessary features of mobile devices including the various sensors, gesture-support, and network facilities [26, 61]. Therefore, enabling a wide range of testing capabilities on mobile devices, similar to GROPG [42], can be useful. Additionally, mobile platforms are becoming increasingly different from one another limiting the creation of platform-independent apps [26, 61]. This problem can be countered by enabling customization of apps on individual phones to use the respective phone’s resources and for deployment on that phone itself in a convenient manner.

One of the challenges in supporting app development on phones is sustaining the interests of users and preventing decreased usage after the initial novelty period, a trend observed in the usage of TouchDevelop [35]. While it is understandable that mobile devices can support creation of apps up to only a certain level of complexity, enabling an expansive set of capabilities and opportunities for creatively building apps using several of the device’s features may help counter this challenge.

Effective use of screen real estate is another challenge in mobile app development. When developing apps on the phone itself, the front-end or UI of the apps can be designed by applying Visual Programming principles (discussed later) to available UI components, similar to the UIBuilder of Mobidev [51], so that developers can directly visualize and manipulate the UI of their apps.

While TouchDevelop [58] is a new language designed for smartphone usage, it is challenging to enable the use of conventional “text-heavy” programming languages, such as Java and JavaScript, for app development on mobile devices. This may require adapting the representation and input mechanisms of these languages for mobile device usage. We present a few ideas for such adaptations in the next section.

**THEME 2: PROGRAMMING-LANGUAGE-DRIVEN INTERFACE DESIGNS**

To overcome the drawbacks of mobile devices, such as small screen space and difficulty using the virtual keyboard, certain papers have turned to finding programming language characteristics that are suitable for use on mobile devices. These characteristics could refer to a language’s programming paradigm, its syntax or other attributes that make it possible for it to be represented compactly, input in various ways, or enable features such as autocompletion [1, 17, 23, 37]. This also includes the language design of TouchDevelop [58] which was developed specifically for smartphone interaction. In this section, we discuss these resulting programming environment designs [17, 23, 37] and tool implementation [1].

**Concatenative Programming languages are tablet-friendly**

Hesenius et al. present a sketch for a development environment to enable programming in Factor on tablets [23]. They opine that productive programming environments for concatenative and stack-based programming languages, such as Forth and Factor, can be developed on space-constrained devices since they have a minimalistic and compact representation unlike imperative programming languages which are text heavy. Additionally, they can also realize the languages’ support for interactive development wherein the design environment has access to the runtime environment and vice versa, allowing code to be modified at runtime. Their prototype sketch shows the tablet screen divided into Factor-specific tools including a program editor, tool for code-navigation, and stack visualizations for the code [23].

\(^1\)https://play.google.com/store/apps/details?id=net.sf.droiddebugger&hl=en
Using speech templates to input Java code

Feldman et al. present ideas for implementing a programming environment, Deverywhere, for existing languages such as Java and JavaScript to be used on smartphones and tablets [17]. Voice and touch input are proposed for program entry, editing and navigation in Deverywhere. This can be achieved by incorporating the programming language’s syntax and semantics, and context-sensitive capabilities in the speech recognition tool [7, 15]. They list a few guidelines for creating speech templates, e.g., saying “for i from zero to n” to input the Java code, for (int i = 0; i<n; i++) on the mobile device and these templates can also be customized to suit the styles of different programmers.

Enabling programming mainly using voice input reduces or eliminates the need for using the soft keyboard [17]. Deverywhere also focuses on providing alternative and compact representations for displaying the code on mobile devices. The design suggestions for code representation include using different colors, fonts, and symbols to distinguish between the program elements, vertical text boxes to show names and extents of functions, background colors to denote scopes, and circular watermarks to denote loops. The examples shown also use bold horizontal lines as delimiters and omit some elements such as braces, types, and certain keywords, such as then, else, class, return, by making their notations apparent in the code graphically.

Keyboard extension to facilitate entering Java code

Almusaly and Metoyer focus on text input and present a block-based keyboard extension for Java program-entry on tablet devices by incorporating the language grammar and the commonly used program constructs found by analyzing Java programs [1]. The main motivation behind this keyboard extension is the difficulty of typing on virtual keyboards, especially for programs containing many numbers, special characters, and symbols. One of the main design decisions made in the keyboard extension is having the keys represent frequently used program constructs rather than characters which enables faster source code input.

This syntax-directed keyboard extension was compared with the standard virtual keyboard with respect to the input of 2 Java programs using 27 participants. The participants made fewer errors and used fewer keystrokes per character using the syntax-directed keyboard extension and also found the keyboard extension to be mentally less demanding than the standard virtual keyboard.

Decomposition of Java programs to facilitate learning

Motivated by the lack of desktops outside classroom environments, Mbogo et al. have developed a mobile application to support university students in learning Java programming [37]. The main interface of the application presents the structural components of typical Java programs and students edit a program component-wise. Static scaffolding learning techniques are utilized in the application wherein component-wise editing is always enforced irrespective of the level of learning attained by the student. For example, beginners are forced to complete components in a certain order while there is no order restriction for more advanced learners but all learners are required to edit the programs component-wise. Tapping a component opens an editor tab where the students edit the respective component and another tab enables them to see the whole program or get an overview of how the components are interconnected.

The application was evaluated using 64 students across three African universities and was deployed on an Android phone with a screen size of 2.8 inches. Overall, the application was deemed useful for learning and the scaffolding technique of constructing a program one part at a time made it easier to program on the small screens.

Discussion

The key challenge here is finding ways to leverage characteristics of programming languages and tasks to support their use on mobile devices and integrating mobile device interaction mechanisms into their usage. The work discussed provides us with a few approaches. For example, Deverywhere [17] borrows from literature on inputting programs by voice that were originally devised for programmers suffering from Repetitive Strain Injury (RSI) and on multiple views or abstractions of code to design their interface. Similarly, we can borrow from existing principles in programming language designs and software engineering. Practices advocating code reuse, e.g., software design pattern, methods for code abstractions including automated refactoring, programming paradigms that enable decomposition of bigger programs into smaller manageable blocks, such as modular programming, structured programming and object-oriented programming, and techniques for concise visual presentation of programs such as code folding can all be used to make programming interfaces mobile-device-friendly and less text heavy.

The aforementioned techniques or programming language designs can be combined with the interaction and input mechanisms of mobile devices to enable more convenient code entry, manipulation, and navigation. For example, instead of plain text, UI blocks, can be used for both code entry and representation. This is observed in the block-based code used in both TouchDevelop [58] and the “syntax-directed” keyboard extension [1] that are easily selectable using finger taps. Pen and touch gestures can be devised for code entry, navigation, display, and for programming tasks such as refactoring (discussed later).

THEME 3: VISUAL-PROGRAMMING-BASED APPLICATIONS

In this section, we present general Visual Programming (VP) concepts and briefly list examples of VP-based environments implemented on mobile touchscreen devices. We focus on the VP concepts because there is a strong association between VP and touchscreen interaction [16, 21, 29].

VP concepts

Visual Programming (VP) languages enable programming by means of interacting with graphical elements, such as blocks, symbols, and arrows, rather than text. They are known,
in general, to promote program comprehension by repre-
senting content in two-dimensions (text is considered one-
dimensional) and by emphasizing the underlying semantics
rather than the syntax [40, 53]. The contexts where VP is
used mostly include learning environments (for both children
and novice programmers) and specialized domains [40, 41].

VP languages are a somewhat natural fit for use on touch-
screen devices because they inherently leverage their inter-
action style and make minimal or no use of the keyboard
[21, 29]. Aspects of VP can be observed even in the syntax-
enforcing implementations of TouchDevelop [58] and the
syntax-directed keyboard extension [1]. Therefore, incorpo-
rating VP concepts in the implementations of even conven-
tional programming languages on touchscreen devices can be
useful in advancing their usability.

**Examples of VP-based environments on mobile devices**

Learning environments are one of the main contexts in which
visual programming (VP) applications are used. VP envi-
ronments, similar to and inspired by those commonly used
in learning contexts for children and young adults, such as
Scratch [50] and Blockly [18], have been implemented or
adapted for use on touchscreen devices such as smartphones
and tablets; examples include ScratchJr [56], Hopscotch [19],
YinYang [38] and Catroid [54]. Ihantola et al. [25] and Kar-
avirta et al. [27] present adaptations of the Parson’s puzzles
web application [46] for use on mobile touchscreen devices;
these block-based puzzles are designed to help students learn
new programming languages.

Hackett and Cox discuss the natural fit between VP and
touchscreen interaction and explore the use of bi-manual in-
teractions on multitouch tablets for a VP environment proto-
type [20, 21]. Essl stresses the need to formulate approaches
that take into account the input and display capabilities of mo-
bile devices for enabling programming on them and presents
an example approach based on data-flow programming for
multitouch mobile devices [16].

Visual programming is also popularly used in building end-
user programming applications [41]. The UIBuilder of Mo-
bidev [51], discussed previously, is also VP-based. Puzzle
[13] is another example of a VP-based end-user programming
application built to enable mobile-app development on mo-
bile touchscreen devices.

Research focused on specific types of VP include Freeform
[47], which is a Visual Basic IDE plug-in based on “diagram-
matic programming” that enables sketching of UI designs us-
ing a stylus on touchscreen devices which are recognized and
converted to code by the underlying IDE.

**Discussion**

The key takeaway from this section is that VP elements such
as blocks, arrows, and other graphical symbols including the
UI components on mobile devices are easily manipulable on
mobile touchscreen devices. Given that VP is said to use
screen space ineffectively when displaying more content or
more complex program structures [41], one of the challenges
in enabling VP on mobile devices with limited screen space
is rendering adequate programming content on them. Aspects
of VP can be also be incorporated in text-based programming
interfaces, i.e. hybrid interfaces, on mobile devices, increasing
their usability by facilitating program entry and compre-
hesion.

**THEME 4: MULTI-DEVICE COLLABORATION**

Mobile devices have also been used as auxiliary, internet-
worked devices in larger programming environments to pro-
vide support for tasks which are inconvenient to achieve using
the IDE alone [45] or to enable new functionality [9].

**Augmenting IDEs with mobile devices to distribute pro-
gramming**

Programmers are frequently faced with tasks such as refac-
toring and code navigation that require them to view and manip-
ulate multiple programming artifacts simultaneously; using
the support provided by IDEs for these tasks can be inconve-
nient [45]. Parnin et al. aim to facilitate such tasks by aug-
menting IDEs with interactive touchscreen devices of varying
form factors including portable devices such as tablets, called
CodePads [45]. Snippets of program content from various
documents can be visualized concurrently on these devices
enabling programmers to view and manipulate artifacts rele-
vant to a particular task in a more convenient fashion without
losing focus.

CodePads generally display program content, enable pen and
multi-touch interactions, provide task-specific functionality,
and communicate and collaborate with the primary IDE [45].
Certain CodePads are better suited for certain tasks. The
task- and CodePad-dependent multi-touch gestures presented
in the paper for different task scenarios include using down-
ward and upward vertical swipe gestures to select and high-
light text, respectively, two-finger gestures to scroll, merge
and split code fragments, expand and shrink gestures for se-
matic zoom, and gestures that communicate with the IDE.
CodePads can also be useful for recording code histories, for
e.g., by combining a chronological visualization of the pro-
gramming activity and code annotations added by the pro-
grammer using pen input.

The designs for content display on CodePads include using
low-fidelity representations for tasks such as navigation
through documents and using high-fidelity representations for
tasks that require manipulation of the program content on the
CodePad. The representation used can also be dependent on
the form factor of the CodePad.

**Connected mobile devices facilitating access to shared
program content during developer meetings**

In the context of developer meetings, the environments gen-
erally come equipped with support for a single presenter or
displaying a single presentation; developers often switch be-
tween different presentations by connecting the projector to
different devices, often disrupting task-focus [9]. CodeSpace
is an environment developed to enable and facilitate some of
the common programming tasks performed during developer
meetings. They support code review, editing and grouping
code fragments, and bug triage by providing capabilities such
as democratic access to program content on a shared display, sharing and transfer of program content between developers’ devices and between the devices and the display, and annotation [9].

**Code Space** combines ‘touch’ and ‘air’ gestures to enable interactions between the developers’ devices and a multitouch shared display during developer meetings [9]. The touch gestures are performed on the developers’ mobile touch devices, laptops with touchscreen displays or on the shared display; the hybrid ‘touch + air’ interactions are enabled with two Microsoft Kinect sensors. The **Code Bubbles**-like representations [10] on the devices are accessed using touch and also provide a mode for annotations. Some of the gestures presented include using a mobile touch device for pointing and manipulating digital objects on the display, bi-manual interactions involving pointing and directional ‘swipe’ gestures to transfer content between a device and a display or between two devices, and vertically holding a mobile device to temporarily display content on the shared display. Typically, in the bi-manual interactions, one hand is used to perform the air gesture (pointing or posture) and the other hand performs the touch gesture on one of the touchscreen devices or display.

A formative study was performed to evaluate **Code Space** with 9 professional developers [9]. Overall, the participants reacted positively to the system and most of the ‘touch + air’ pointing gestures were deemed socially acceptable by the participants except the gestures for peer-to-peer transfer where they were required to point at a colleague.

**Discussion**

Mobile devices come equipped with a multitude of unique sensors and features which can be leveraged to enable new functionality that are either absent or impossible to implement in conventional programming environments. The challenge lies in exploiting their features and connectedness to explore the opportunities they present for novel applications in programming contexts.

Connected mobile devices can be especially useful in facilitating collaborative tasks and in distributing programming. Traditional IDEs are generally seen as the domain of individual programmers and contain features that are not conducive to collaborative work [22]. Mobile devices can enable “software peer review” wherein all the team members review the same code on their respective devices and their inputs are made visible to others. A small-scale version of this problem, pair-programming, has been addressed in **CodeGraffiti** [36] which is discussed in the next section.

Traditional IDEs provide support for a wide variety of programming tasks by incorporating numerous tools but it has been observed that programmers, generally, are either unaware or do not make optimal use of many of these tools [34, 52]. Given that the features included in the IDEs can be cognitively demanding and overwhelming, it can be useful to focus on individual tasks independently by distributing them on peripheral connected mobile devices, also supporting “separation of concerns” [24], similar to the approach in **CodePads** [45].

**THEME 5: AIDS FOR CODE COMPREHENSION**

Programmers exhibit a behavior, both when working independently and during tasks involving collaboration, wherein they often use elements external to the IDE such as paper or whiteboards for taking notes or drawing sketches to complete programming tasks [12, 34, 44]. In this section, we present past work that addresses this behavior and attempts to make these usually transient notes and sketches persistent with the help of mobile touchscreen devices.

**Pen-based code annotations and linking images to code**

Aids for code comprehension include enabling pen-based annotations (the annotations remain attached to the respective code segments despite dynamically changing code) in the IDE [11, 36, 57, 47, 48] and linking images (taken using the camera) containing sketches to code in the IDE [5]. Pair-programming, where two programmers collaborate to solve programming tasks, is addressed in **CodeGraffiti** [36] by enabling sketching and annotation on a peripheral tablet device used by the non-coder while the same code view is shared on both the coder’s computer and the tablet device.

**Discussion**

Studies have found that programmers spend more time reading and comprehending code as part of maintenance tasks than they do writing code [30]. These behaviors can be advantageous for mobile devices provided sufficient aids for program comprehension are incorporated. These aids can range from minor changes in the code representation such as including syntax coloring (or highlighting) and indentation to providing program visualizations such as the call graph. Additionally, tools for browsing from high-level views to low-level details and vice versa, search tools, and context-driven views can be helpful [55]. Some of these tools are also included in **CodePads** [45] and **Code Space** [9].

Ideas for tools to incorporate on mobile devices to facilitate code comprehension can be drawn from the tools included in IDEs [6, 55] and adapting them appropriately for use on mobile devices. Many of these tools are also programming-language-dependent, such as syntax-coloring. Mobile device features can also be leveraged to provide novel functionality, such as linking camera images to code [5]. Augmented reality techniques could be implemented to give collaborating developers a personal window into the source code overlaid with additional comprehension information such as highlighting potential code smells.

**THEME 6: GESTURES FOR PROGRAMMING TASKS**

Touch-based gestures have been formulated for programming tasks such as refactoring, either in an effort to add touch support to traditional IDEs [4, 8], or to be used as part of programming environments on mobile touchscreen devices [49].

**Gestures formulated based on guidelines**

Biegel et al. [8] present design decisions for optimizing the GUI of the **Eclipse** IDE for touch access and a set of touch gestures for common refactoring tasks. These gestures were devised based on the guidelines for mapping gestures to refactorings provided by Murphy-Hill et al. [39].
An evaluation with 8 participants was done to assess the gestures formulated for refactoring [8]. The users were asked to perform certain refactoring tasks using the traditional keyboard and mouse setup and using the formulated gestures both on a touch monitor as well as on a tablet. Most of the users did not remember the shortcuts for the tasks and spent a considerable amount of time (between 5 to 15 seconds) to find the respective commands in the IDE menu in the traditional setup. On the other hand, the users quickly learned and used the gestures on the touch devices but found that it was hard to select text because of the impreciseness of touch.

**Touch and pen gestures elicited from users**

In *RefactorPad*, Raab et al. present a gesture set for common editing and refactoring tasks that can be used as part of development environments on touchscreen devices [49]. The gesture set presented was obtained from a guessability study similar to that described by Wobbrock et al. [62]. The study was designed to elicit both pen and touch gestures from the participants for a list of non-programming-language-specific editing and refactoring tasks which was compiled by studying various editors including *Eclipse*, *Sublime Text*, *Visual Studio* and *Xcode*. The study results showed that more participants preferred to use the pen for performing the gestures and participants often used the same gestures using both touch and pen input for a given task. Multitouch gestures were used for only a few tasks. The interaction behaviors of the participants also appeared to be influenced by the mobile operating systems (*Android* or *iOS*) they were most familiar with.

The programming-specific gestures for touch-enabled IDEs presented by Bačíková et al. include some of the existing general purpose gestures used in *Android* and *iOS* multitouch platforms, new general purpose gestures enabling certain IDE features such as code folding and semantic zoom, and ‘drawn’ gestures elicited from users for various program constructs such as class declaration and loop statements [4].

**Discussion**

Gestures are one of the primary interaction techniques used on mobile devices. The programming tasks mentioned above are normally performed in IDEs using either keyboard shortcuts, typing, selecting items from long menus, or a combination of these. While keyboard shortcuts and menu-based approaches are far from intuitive, gestures have the potential to be more intuitive, guessable, and memorable [8, 32, 43].

Gestures can be devised, for example, to perform tasks such as refactoring or to enter code or enable different functionality depending on the context. However, they will have to be designed carefully and standardized over time to be “usable” [43]. Elicitation studies, such as the ones mentioned above, provide a good method to define gesture-sets that are reflective of user behaviors in a particular context [62]. Based on the observations in the above studies, it may be good practice to design gestures that are consistent with the mobile operating systems on which they will be used [4, 49]. Additionally, pen-based gestures can be used for text-manipulation tasks because of their greater precision and ease of use [49].

**SUMMARY AND FUTURE DIRECTIONS**

The utility of mobile touchscreen devices in programming situations has not been regarded with much enthusiasm. We have not only reviewed promising uses for these devices in programming, but also hinted at the space of unexplored capabilities of these devices in these contexts. Their ubiquity and features allow them to favorably permeate contexts ranging from solo programmers’ workspaces to larger interactive programming environments.

Mobile devices can, for example, be equipped with functionality that uses the camera to sense the source code displayed external to the mobile device (e.g. on a white board) and automatically present related content, such as last commit or who’s working on it now. It can suggest refactoring, or highlight potential code smells - all on the personal mobile device of one developer without disturbing the shared view. Location sensing on the devices can be used to detect if users are travelling, enable access to their code and automatically synchronize changes with the desktop version.

While reinventing the wheel is not necessary to enable usable programming on mobile devices and a number of existing practices and designs from conventional programming environments can be used to incorporate programming functionality on mobile devices, these practices and designs will have to be adapted to suit the interaction style of mobile devices. Mobile devices come equipped with many features that allow for numerous designs wherein gestures can replace operations commonly performed with the mouse, multimodal input can be used for program entry and editing, and the GUI elements can be visualized in various ways.

The six themes presented in the survey are not independent and enabling usable programming conforming to any theme would require borrowing ideas from multiple themes. For example, mobile app development environments can benefit from existing programming language designs adapted to enable convenient code entry and manipulation on the devices. Connected mobile devices can be used for collaborative tasks such as code review as described in the multi-device collaboration theme. This requires enabling task-specific functionality on the devices and aids for code comprehension such as search and navigation tools and code visualizations that are specific to the task. These aids may also be programming-language-dependent and use the language’s syntax and semantics to provide the necessary visualizations.

There are numerous studies on the behaviors of programmers as well as the functionality and features of conventional IDEs [31, 33, 34, 44]. These studies can serve as useful starting points to identify if any shortcomings in the conventional programming setups can be mitigated by integrating mobile devices or if mobile devices can enable novel interaction or programming capabilities in these environments.

There are also many research topics that need to be explored in reference to the programming languages that can be supported on mobile devices. It is known that traditional IDEs have been designed keeping in mind the interaction style (WIMP) of the mouse and keyboard [49] but it is unclear...
whether conventional programming language designs also have strong affinities with the interaction style of desktops. The extent of these affinities may play a role in determining their usability and adaptation for use on mobile devices.

In summary, we have presented the diverse body of research with respect to using mobile touchscreen devices for programming, identified the main themes of contributions, and presented the programming capabilities supported, the interaction capabilities of the devices leveraged, and users’ acceptance of the implementations in each theme. We have identified key challenges and presented potential directions for future work. As researchers move forward in exploring the use of mobile devices in programming contexts, we hope this survey can serve as a starting point to understand what has been done and a roadmap for areas that should be further explored.

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| Mobile device types | Role of mobile devices | Programming Language | Type of implementation or prototype | Programming support | Interaction types | User studies |
|---------------------|------------------------|----------------------|------------------------------------|---------------------|------------------|-------------|
| Smartphones         | Primary                | Imperative programming | Standalone programming environment | Debugging          | Touch + Speech    | Longitudinal study |
| Tablets             | Auxiliary              | Concursive programming | Mobile app development-based       | Software build tools| Touch + Pen       | Usability study |
|                     |                        | New programming language | Web-based             | Code Annotation    | Elicitation study |             |
|                     |                        | Visual programming specific | Structured editing   | Refactoring tasks | Touch + Speech    |             |
|                     |                        | New programming language specific | Code Anotation        | Collaborative tasks (e.g., code review and pair-programming) | CodeSpace [9] |             |
|                     |                        | New programming language specific | Auto-completion       | Visual representations for code comprehension | Code annotation papers [57, 48, 11] | Aids for Code Comprehension |
|                     |                        | New programming language specific | IDE-based            | Debugging          | CodeGraffiti [36] |             |
|                     |                        | New programming language specific | Mobile app development-based | Visual representations for code comprehension | SketchLink [5] | SketchLink [5] |
|                     |                        | New programming language specific | Web-based             | Software build tools | Touch + Pen       | Gestures for Programming Tasks |
|                     |                        | New programming language specific | Mobile app development-based | CodeGraffiti [36] | CodeSpace [9] | Multi-device Collaboration |
|                     |                        | New programming language specific | Web-based             | Code annotation papers [57, 48, 11] | Code annotation papers [57, 48, 11] | Aids for Code Comprehension |
|                     |                        | New programming language specific | Mobile app development-based | Debugging          | Touchifying an IDE [8] | Touchifying an IDE [8] |
|                     |                        | New programming language specific | Web-based             | Code annotation papers [57, 48, 11] | CodeSpace [9] | Aids for Code Comprehension |
|                     |                        | New programming language specific | Mobile app development-based | Debugging          | Touchifying an IDE [8] | Touchifying an IDE [8] |
|                     |                        | New programming language specific | Web-based             | Code annotation papers [57, 48, 11] | CodeSpace [9] | Aids for Code Comprehension |
|                     |                        | New programming language specific | Mobile app development-based | Debugging          | Touchifying an IDE [8] | Touchifying an IDE [8] |
|                     |                        | New programming language specific | Web-based             | Code annotation papers [57, 48, 11] | CodeSpace [9] | Aids for Code Comprehension |
|                     |                        | New programming language specific | Mobile app development-based | Debugging          | Touchifying an IDE [8] | Touchifying an IDE [8] |
|                     |                        | New programming language specific | Web-based             | Code annotation papers [57, 48, 11] | CodeSpace [9] | Aids for Code Comprehension |
|                     |                        | New programming language specific | Mobile app development-based | Debugging          | Touchifying an IDE [8] | Touchifying an IDE [8] |
|                     |                        | New programming language specific | Web-based             | Code annotation papers [57, 48, 11] | CodeSpace [9] | Aids for Code Comprehension |
|                     |                        | New programming language specific | Mobile app development-based | Debugging          | Touchifying an IDE [8] | Touchifying an IDE [8] |
|                     |                        | New programming language specific | Web-based             | Code annotation papers [57, 48, 11] | CodeSpace [9] | Aids for Code Comprehension |
|                     |                        | New programming language specific | Mobile app development-based | Debugging          | Touchifying an IDE [8] | Touchifying an IDE [8] |
|                     |                        | New programming language specific | Web-based             | Code annotation papers [57, 48, 11] | CodeSpace [9] | Aids for Code Comprehension |

Table 1. Summary of the survey listing the papers that use mobile touchscreen devices for programming and the themes they fall under (rows) and the key attributes of their contributions (columns)