Morphology
https://doi.org/10.1007/s11525-023-09413-8

The primacy of morphology in English braille spelling: an analysis of bridging contractions

Robert Englebretson[1] · M. Cay Holbrook[2] · Rebecca Treiman[3] · Simon Fischer-Baum[4,5]

Received: 16 September 2022 / Accepted: 14 June 2023

Abstract

This study examines the use of braille contractions in a corpus of spelling tests from braille-reading children in grades 1-4, with particular attention to braille contractions that create mismatches with morphological structure. Braille is a tactile writing system that enables people who are blind or visually impaired to read and write. In English and many other languages, reading and writing braille is not simply a matter of transliterating between print letters and their braille equivalents; Unified English Braille (the official braille system used in the United States, Canada, the United Kingdom, and several other English-speaking countries) contains 180 contractions—one or more braille cells that represent whole words or strings of letters. In some words, the prescriptive rules for correct braille usage cause contractions to bridge morphological boundaries and to obscure the spellings of stems and affixes. We demonstrate that, when the prescriptive rules for correct braille usage flout morphological structure, young braille spellers generally follow the morphology rather than the orthographic rules. This work establishes that morphology matters for young braille learners. We discuss the potential impact of our findings on braille research, development, and pedagogy, and we suggest ways in which our findings contribute to understanding the nature of orthographic morphemes and the place of braille in the reading sciences.

Keywords Braille · Braille contractions · Bridging · Morphology · Morphological awareness · Spelling · Unified English Braille

✉ R. Englebretson
reng@rice.edu

1 Department of Linguistics, Rice University, Houston, TX, USA

2 Department of Educational and Counseling Psychology and Special Education, University of British Columbia, Vancouver, BC, Canada

3 Department of Psychological and Brain Sciences, Washington University, St. Louis, MO, USA

4 Department of Psychological Sciences, Rice University, Houston, TX, USA

5 National Science Foundation, Social, Behavioral, and Economic Sciences Directorate, Alexandria, VA, USA

Published online: 14 July 2023

1 Introduction

Morphology matters. A substantial body of research in recent decades has demonstrated that morphological knowledge is a crucial component of learning to read and write. Implicit recognition of a variety of patterns, including mappings between orthography and morphology, constitutes much of one's knowledge of a writing system (Kessler & Treiman, 2015; Treiman & Cassar, 1996). In spoken English, a stem may be pronounced differently when affixed by a derivational morpheme, such as the stem 'sign' in 'signal' or the stem 'magic' in 'magician'. However, in written English, the stems in these derived forms are spelled alike regardless of pronunciation. In these cases, orthography is based in morphological regularity rather than strictly following the phonology, and the consistent spelling of the stem across these words serves to facilitate word recognition. Detection of orthographic morphemes enables skilled readers to recognize words based on regularities of form and meaning, despite irregular grapheme-phoneme correspondences or historical sound changes (Rastle, 2019; Treiman & Bourassa, 2000; Venezky, 1999). There are of course counterexamples, e.g., 'explain'/'explanation', 'pronounce'/'pronunciation', where spelling follows phonology rather than morphology. However, stem conservation (i.e., the consistent spelling of stems across different morphological contexts) is well attested in the writing systems of English and numerous other languages (for a systematic review from a cross-linguistic perspective, see Chliounaki, 2007; Sandra, 2022). Generalizing the meanings of recurring stems and affixes across words, and recognizing the conservation of stems in derivational contexts, bootstraps the learning process and facilitates reading and spelling (Bahr et al., 2020; Carlisle 1988, 1995, 2000, 2003; Nagy et al., 2014; Rastle et al., 2000; Rubin, 1988; Sandra, 2022). Explicit teaching of morphological patterns is positively correlated with improvement in reading and spelling (Burton et al., 2021; Bryant et al., 2006; Kemper et al., 2012. For systematic reviews, see Bowers et al., 2010; Carlisle et al., 2010; Goodwin & Ahn, 2013). In sum, correspondences between morphology and spelling enable readers to implicitly recognize the same stems in different morphological environments and to generalize their meanings across multiple word forms.

Since morphology plays a strong supporting role in reading and spelling, an interesting question emerges when a writing system happens to have prescriptive orthographic rules that are at odds with the language's morphology. When orthography and morphology conflict, do young spellers primarily rely on the orthographic rules they are being taught and the exemplars they naturally come across while reading, at the expense of morphological regularity? Or, do they violate these prescriptive orthographic rules and instead spell words in ways that conserve morphological structure? Unified English Braille is a writing system that facilitates examination of exactly this question. By analyzing data from an international braille spelling contest held annually in the US and Canada, we demonstrate that young braille learners' implicit knowledge of morphology tends to take precedence over prescriptive orthographic rules: Spellers conserve stems and affixes to a statistically significant degree in words where the prescriptive orthographic rules would dictate they should do otherwise.

Braille is a tactile writing system that enables people who are blind or visually impaired to read and write. (For a general overview of braille as a writing system and a discussion of its place in the reading sciences, see Englebretson et al., 2023.) The braille script is based on a raised 6-dot cell ⠿. In English (and many other languages), combinations of these 6 dots transliterate the corresponding print alphabet: ⠁ ⠃ ⠉ ⠙ ⠑ = a b c d e, etc. English braille that transliterates print spelling is called uncontracted (or Grade 1) braille, and is only used in limited contexts, such as for (some) early learners, for (some) individuals with intellectual disabilities, or for (some) adults with vision loss who formerly read print and wish to learn braille primarily for use in tasks such as labeling their household items or recognizing basic numbers on door and elevator signs.

In English (and many other languages), becoming a fully literate reader and writer of braille also entails learning a set of language-specific braille contractions—one or more braille cells that represent whole words or strings of letters. This is called contracted (or Grade 2) braille, and is the system for almost all contexts aside from the ones described above. Contracted braille is used for most literature and educational materials, publications from blindness organizations and braille publishing houses, and is the grade of braille required on signage under the Americans with Disabilities Act in the United States.

Unified English Braille, the official braille system currently in use in most English-speaking countries including the United States and Canada, contains 180 contractions. Examples of contractions include ⠮ 'THE', ⠫ 'ED', ⠂ 'EA', ⠐⠑ 'EVER', and ⠸⠍ 'MANY'. As a result of contractions, the orthographic representations of a word in print may differ substantially from that same word's orthographic representation in braille. For example, the English word written in print as 'standardization' contains 15 letters, while in contracted braille it contains only nine cells: ⠌⠯⠜⠙⠊⠵⠁⠰⠝ 'ST.AND.ARdizaTION'.[1] Braille contractions are prescriptively defined based on a list of usage rules, example words, and exceptions, as set forth by the Braille Authority for a given country or region. In the United States and Canada, this standards-setting body is the Braille Authority of North America, a member of the International Council on English Braille (ICEB). The current rules of Unified English Braille contractions are codified in the official rulebook published by ICEB (Simpson, 2013).

Braille contractions are required to be used whenever the sequence of letters they represent occurs in print, unless a usage rule specifies otherwise or the specific word appears on the list of exceptions in the rulebook. For example, ⠮ 'THE' stands alone as the English word 'the', represents this sequence of letters in words like ⠮⠗⠁⠏⠽ 'THErapy', ⠃⠗⠕⠮⠗ 'broTHEr', and ⠃⠁⠮ 'baTHE', and even in words where it crosses a syllable and morpheme boundary such as ⠌⠗⠢⠛⠮⠝ 'STrENgTHEn'. ⠫ 'ED' stands alone as the name 'Ed' or the abbreviation 'ed.'. It occurs in monomorphemic words like ⠫⠊⠞ 'EDit', ⠓⠫⠛⠑ 'hEDge', and ⠗⠫ 'rED'. It occurs in words like ⠝⠑⠫ 'neED' and ⠛⠗⠑⠫⠽ 'greEDy' (where it disrupts the digraph 'ee'). It represents the regular past-tense suffix on most verbs, e.g., ⠌⠁⠍⠏⠫ 'STampED', ⠋⠁⠊⠇⠫ 'failED', and ⠺⠁⠝⠞⠫ 'wantED'. And, as we will discuss shortly, it can cross sublexical boundaries in words like ⠗⠫⠳⠃⠇⠑ 'rED.OUble' and ⠋⠗⠑⠫⠕⠍

[1] Throughout this article, we use the following conventions for glossing the braille examples in print: Braille contractions are transliterated using small capital letters; adjacent braille contractions are separated from one another by a period; and direct transliterations of braille letters are in lowercase.

‘freEDom’. ⠸⠍ ‘MANY’ stands alone as the English word ‘many’, but also occurs in the morphologically-unrelated name of the country ⠠⠛⠻⠸⠍ ‘G.ER.MANY’. In sum, contractions are defined in terms of sequences of letters, and generally are used without respect to pronunciation, meaning, or sublexical structure, unless the rulebook specifies otherwise. For example, the rulebook provides a consistent exception for compound words, disallowing contractions from crossing boundaries between stems: “Do not use a groupsign which would bridge the words which make up an unhyphenated compound word” (Simpson, 2013, p. 146). E.g., ⠹ ‘TH’ is not permitted in ‘boathouse’, ‘foothold’, and ‘anthill’.

Because braille contractions generally represent strings of letters wherever they happen to occur, their usage is typically not constrained by sublexical units such as digraphs, syllables, and morphemes. As a few of the examples in the previous paragraph have illustrated, sometimes the letters on either side of a morpheme boundary happen to correspond to the letters comprising a contraction. This leads to cases of morphological bridging, where braille contractions merge the stem and affix, leading to neither morpheme being recognizable. For example, the English word represented in print as ‘redouble’ is written in braille as ⠗⠫⠳⠃⠇⠑ ‘rED.OUble’ (Simpson, 2013, p. 149). The ED contraction bridges the prefix-stem boundary, and obliterates the spellings of both the prefix ‘re-’ and the stem ‘double’, since there is neither an ⠑ ‘e’ nor a ⠙ ‘d’ in this word, only the symbol ⠫. Neither the prefix nor the stem is conserved in this morphologically complex word, and a reader cannot immediately recognize either of these morphemes. Another example of morphological bridging occurs in the English word written in print as ‘mileage’, which is written in braille as ⠍⠊⠇⠂⠛⠑ ‘milEAge’ (Simpson, 2013, p. 151). The EA contraction bridges the stem-suffix boundary, obliterating the spellings of both the stem ‘mile’ and the suffix ‘-age’. There is neither an ⠑ ‘e’ nor an ⠁ ‘a’ in this word, only the symbol ⠂. Again, neither the stem nor the suffix is conserved, and so a reader cannot immediately recognize either of these morphemes based on their spellings. The morphologically-bridged words ⠗⠫⠳⠃⠇⠑ ‘rED.OUble’ and ⠍⠊⠇⠂⠛⠑ ‘milEAge’ contrast with morphologically complex words that are not bridged, such as ⠗⠑⠏⠁⠽ ‘repay’ or ⠋⠗⠕⠝⠞⠁⠛⠑ ‘frontage’, since the letters <ep> and <ta> do not happen to make up a contraction. These two words contain no bridging contractions, and so stems and affixes are immediately apparent—the prefix ‘re-’ and the stem ‘pay’, and the stem ‘front’ and the suffix ‘-age’, respectively.

Unlike the print counterexamples to stem conservation cited earlier (‘explain’/’explanation’, ‘pronounce’/’pronunciation’), where the lack of morphological conservation is balanced by a spelling that is phonologically motivated, there is no phonological motivation for the use of bridging contractions. For example, ⠫ ‘ED’ in ⠗⠫⠳⠃⠇⠑ ‘rED.OUble’ interferes with both morphology and phonology. While the usual pronunciation of this prefix is /ɹi/ (or /ɹə/ when unstressed), here, ⠗⠫ ‘rED’ suggests the word ‘red’ with the corresponding pronunciation /ɹɛd/. In sum, morphological bridging is solely motivated by the prescriptive orthographic rule to use a contraction whenever the corresponding sequence of letters occurs, and it simultaneously flouts both morphology and phonology.

To our knowledge, there have only been two previous studies that have begun to address the interplay between English braille contractions and morphology. In an unpublished PH.D. dissertation, Lauenstein (2007) argued that implicit knowledge of linguistic structure has a greater influence on braille users than do the explicit rules for the use of braille contractions. The dissertation analyzed the error patterns of a group of 19 braille users (ages 11-42) in the United Kingdom who participated in a carefully-controlled writing study. Among the findings relevant to morphology, subjects tended to perform best when a contraction directly aligns with a morpheme (e.g., when the ⠫ ‘ED’ contraction represents the past-tense suffix -ed as compared to when it represents an arbitrary sequence of the letters ‘e’ and ‘d’). Our current study, on the other hand, focuses on contractions that bridge morpheme boundaries and thus do not align with sublexical units at all. In the other relevant previous study, Fischer-Baum and Englebretson (2016) offered evidence based on lexical decision tasks that English braille readers are sensitive to sublexical structure, and that contractions which bridge morphological units negatively affect word recognition. Specifically, proficient adult braille readers showed slower reaction times and made more errors with morphologically-bridged braille words like ⠗⠫⠗⠁⠺ ‘rEDraw’ than they did with morphologically-transparent braille words like ⠗⠑⠏⠁⠽ ‘repay’. Our current work moves beyond these findings in two ways. First, we ask whether young braille users (grades 1-4) also show sensitivity to morphology, as we cannot assume that findings with adult subjects would directly apply to young braille learners, whose orthographic knowledge is still developing along with their acquisition of literacy. Secondly, while Fischer-Baum and Englebretson (2016) sought evidence for morphological knowledge in perception through lexical decision tasks in braille reading, our current work seeks further evidence for morphological knowledge in braille writing.

Our current study analyzes contraction use in a longitudinal corpus of braille spelling tests of children in grades 1-4. Since there is no prior psycholinguistic evidence examining the factors that influence whether or not braille users correctly use contractions in general, we first seek to determine the factors that influence contraction use overall. Then, in order to examine the interplay between morphological structure and the prescriptive rules of braille contractions, we focus on exactly those words in the corpus where a braille contraction is required to bridge the morphological boundary between a stem and an affix. We ask whether, when a contraction bridges a morphological boundary, young braille spellers significantly fail to use that contraction, as compared to their use of that same contraction when it occurs tautomorphemically (internal to a single morpheme), and whether morpheme bridging influences the use of contractions above and beyond the effects of other variables that correlate with contraction use.

2 Materials and methods

Blindness is a low-incidence disability among children and youth, and the sparse and distributed population of braille users poses challenges for conducting research on braille (Wright, 2010). There are no systematic counts or verifiable data concerning the number of students learning braille or the number of braille readers in the United States (Sheffield et al., 2022). Most students with blindness and visual impairments in the United States and Canada are included in general-education classrooms, and are typically taught braille reading and writing by a qualified Teacher of Students with

Visual Impairments (TVI), who often works as an itinerant teacher across multiple schools. While it is possible to conduct research on adult braille users by recruiting participants at summer conventions of blindness organizations where hundreds of braille readers may be present in the same location (cf. Fischer-Baum & Englebretson, 2016), gatherings of hundreds of braille-learning children are nonexistent. Instead, for research with children learning braille, studies seeking a large sample size have typically been conducted across multiple sites in multiple states (cf. Wall Emerson et al., 2009). As one means of addressing this challenge, our research team is currently creating a longitudinal corpus of braille from students in grades 1 through 12 who participate in the annual Braille Challenge contest sponsored by the Braille Institute of America. This corpus will be available as an open-access resource for use by braille researchers, and is planned to consist of at least seven years of writing samples, spelling tests, and responses to test prompts from several thousand students in the United States and Canada. The corpus will also include deidentified ethnographic information and metadata, and unique participant numbers for each student so as to facilitate longitudinal analyses.

Section 2.1 presents a general overview of the Braille Challenge contests which make up the Braille Challenge Research Corpus, Sect. 2.2 describes the subset of the spelling corpus we are using for this study, and Sect. 2.3 gives an overview of the target words and contractions in the subcorpus that form the basis for our analyses.

2.1 Overview of the Braille Challenge

The Braille Challenge is an annual academic contest sponsored by the Braille Institute of America to promote the learning and use of braille. The contest is open to braille-reading students in grades 1 through 12 who reside in the United States and Canada, and is divided into five levels by grade: Apprentice (1st and 2nd grade), Freshman (3rd and 4th grade), Sophomore (5th and 6th grade), Junior Varsity (7th, 8th, and 9th grade), and Varsity (10th, 11th, and 12th grade). Some students are allowed to participate below grade level, for instance if they are new to braille after having begun their schooling as print readers, or if they have additional circumstances classifying them as reading significantly below grade level; these students' contests are flagged as 'below grade level' and are excluded from our analysis. Approximately 1,000 students across all grade levels participate annually in the Preliminaries, which take place during the first quarter of the calendar year, either as regional events or individually proctored in a local school by a student's TVI. The top ten scorers from each of the five contest levels then compete in the Braille Challenge Finals in June, which typically take place in person near the Braille Institute headquarters in Los Angeles, California. Finalists generally have all travel expenses covered through local and national fund raising, and top finalists receive awards, which may include prizes such as savings bonds and braille-related technology. The Braille Challenge serves as a source of motivation to learn and use braille, contributes to students' pride in braille literacy, and celebrates student achievement.

Each year's Braille Challenge contest consists of a series of written tests, which are identical for all students at the same level. Three of these tests involve reading braille and answering a series of multiple-choice questions: Proofreading, Reading

Comprehension, and interpretation of Charts and Graphs. A fourth test involves writing braille: Spelling for students at the Apprentice and Freshman levels, and Speed and Accuracy (writing passages in braille from dictation) for the Sophomore through Varsity levels. All students write their test responses in hardcopy braille using 6-key input on a Perkins Brailler, a typewriter-like device which has been the standard means of writing braille in the United States and Canada since the 1950s. The hardcopy answers are scored regionally, and then mailed to the Braille Institute where they are checked and used for determining the students who will compete in the Finals. Our research team is currently digitizing the hard copy responses from seven years of Braille Challenge contests, 2017-2023, which will comprise the Braille Challenge Research Corpus.

2.2 The spelling subcorpus

The analyses reported here focus on the spelling contests from at-grade-level students in the 2018, 2019, and 2020 Apprentice Level Preliminaries (grades 1-2), and the spelling contests from the 2018, 2019, 2020, and 2021 Freshman Level Preliminaries (grades 3-4). These are the years that are currently available in the corpus. We focus on the Preliminaries since these reflect the full range and diversity of spellers at each level.

As is typical for English spelling tests for blind and visually-impaired students, learners are expected to write each word in both contracted and uncontracted braille. The rationale for this reflects the reality of most braille users' literacy needs. Students need to know the print (uncontracted) spelling of a word for typing on a QWERTY keyboard and communicating with the broader print-based world; and students need to know the contracted form, as this is what the student encounters while reading, and is what the student must produce when writing braille.

Each spelling test in the Braille Challenge Preliminaries contests contains 40 items, selected by a team of TVIs to reflect a relatively challenging set of words for students at each level. The spelling tests take place with one or more students, each of whom is provided a Perkins Brailler and several sheets of paper. A test proctor reads the instructions to the students, administers the test, and collects the papers. Proctors follow a strict written protocol for administering the spelling tests. The proctor reads the word aloud, then reads a sentence containing the word, and then reads the word a final time, after which the student writes the word in braille. In the instructions before the test begins, students are directed to write each word in uncontracted braille followed by contracted braille. (If the word has no contractions, then the student only writes the uncontracted form.) Students are told that if they wish to make a correction, they should rewrite the word, and only the last instance will be counted. For our analysis, we take the final production of a word without any contractions as the uncontracted response, and the final production of a word with at least one contraction as the contracted response. These are also the responses which the Braille Challenge graders count.

2.3 Items for analysis

The design of the spelling tests allows us to look at a student's contraction use. The uncontracted response reflects a student's knowledge of the print spelling of a word—

specifically the knowledge of whether the word contains the letter combinations that a contraction represents. For example, if the target word is ⠱⠊⠗⠇ 'WHirl', and if a student produces the uncontracted spelling incorrectly as 'werl' or 'wirl', we cannot anticipate that the student would produce a contracted spelling using the contraction ⠱ 'WH' since there is no evidence that the student knows this word contains a 'wh' in the print/uncontracted spelling. Our analysis, therefore, is focused on the unit of the contraction, and takes as a baseline only those instances in which the uncontracted spelling includes the correct spelling of a contraction's constituent letters. This methodological choice should not necessarily be taken to imply that braille users first think of the uncontracted spelling and then apply rules to arrive at the contracted form; the relationship between uncontracted and contracted braille is a question to which we will return in Sect. 5.1. For purposes of our analysis, though, we use uncontracted spelling as a comparative baseline to determine rates of contraction use across all words.

A contraction may comprise one cell, where a single braille cell represents multiple letters (e.g., ⠱ 'WH', ⠮ 'THE', ⠡ 'CH', etc.); or more than one cell, where two or more adjacent braille cells represent multiple print letters (e.g., ⠰⠝ 'TION', ⠊⠍⠍ 'IMMEDIATE', etc.). For this study, we restrict our analysis to one-cell contractions, as these are the only type of contraction found in morpheme bridging. From the 280 words in the spelling contests (40 words per test, 7 tests total), we extracted all words that contain one or more one-cell contractions. Nine words are repeated in multiple years (e.g., ⠱⠔⠑ 'WH.INe', ⠋⠗⠑⠫⠕⠍ 'freEDom'); we included all instances of the word in the analysis. One word ⠌⠁⠍⠏⠫⠫ 'STampED.ED' is excluded from analysis because it contains the same contraction twice, and the adjacent repetition of the same contraction within a single word would pose a problem for our coding, as we would be unable to systematically determine which of the ⠫ 'ED' contractions in the target is correct if only one was produced in the response. Three additional words, ⠛⠻⠃⠊⠇ 'gERbil', ⠃⠗⠪⠎⠻ 'brOWsER', and ⠛⠇⠥⠬ 'gluING', are excluded because they are not found in the lexicon used to estimate word frequency. And ⠎⠅⠊⠬ 'skiING' is excluded because we are unable to estimate bicell transition probability for this word from the CELEX database (Baayen et al., 1993), which we converted to braille. There are 113 words that contain no one-cell contractions, either because they naturally have no contractions (e.g., ⠛⠥⠑⠎⠎ 'guess'), or because they contain only multi-cell contractions (e.g., ⠓⠑⠇⠏⠨⠇⠰⠎ 'helpFUL.NESS', which contains two two-cell contractions). The remaining 162 words comprise 118 words with a single one-cell contraction (e.g., ⠃⠜⠛⠑ 'bARge'), 38 words with two one-cell contractions (e.g., ⠉⠜⠞⠱⠑⠑⠇ 'cARtWHeel'), and six words with three one-cell contractions (e.g., ⠏⠻⠏⠢⠙⠊⠉⠥⠇⠜ 'pERpENdiculAR'). Altogether, these 162 words contain a total usage of 212 one-cell contractions, comprising 23 unique one-cell contraction types. These range in frequency from a single occurrence in all spelling words in the corpus (e.g., ⠖ 'FF' in the word ⠃⠥⠖⠁⠇⠕ 'buFFalo') to 22 occurrences (⠻ 'ER', e.g., in words such as ⠉⠑⠇⠻⠽ 'celERy').

Three of these one-cell contractions bridge a morpheme boundary between a stem and an affix in a total of five spelling words in the corpus: the ED contraction in ⠏⠗⠫⠊⠉⠰⠝ 'prEDicTION' and in ⠋⠗⠑⠫⠕⠍ 'freEDom' (a word which occurred on both the 2018 Freshman and the 2019 Apprentice Spelling tests), the

EN contraction in ⠺⠻⠢⠄⠞ ‘wER.EN’t’, and the ST contraction in ⠍⠊⠌⠕⠕⠅ ‘miSTook’.

We conduct two analyses using these data. First, in Sect. 3, we determine the primary variables that contribute to whether or not a speller uses a contraction, including variables about the specific task and participants, variables about the contractions themselves, and variables about the specific word being spelled. Then, in Sect. 4, which comprises the central part of our study, we analyze the morpheme-bridging contractions in the corpus to determine whether morpheme bridging contributes to the use or non-use of contractions beyond the effects of the other variables. The Open Science Framework page for the current project (https://osf.io/dz6p4) contains the data used in both analyses and the code used to run statistical analysis in R.

3 Analysis 1: variables contributing to contraction use

Ultimately, the goal of our analysis is to determine whether participants are less likely to correctly use contractions when they bridge morpheme boundaries than when they do not. However, there is no prior psycholinguistic evidence examining the factors that influence whether or not braille users correctly use contractions in the first place. This general question must be addressed before we can focus on the specific issue of contractions that bridge morpheme boundaries. In this section, we seek to determine the factors that influence the use of one-cell contractions overall. Then, in Sect. 4, we analyze whether morpheme bridging influences contraction use above and beyond these factors.

3.1 Variables

The variables we consider in this analysis are roughly divided into three categories—task level variables, contraction level variables, and word level variables. We treat some variables in our analysis as fixed effects and others as random effects.

3.1.1 Task level variables

Four task level variables are considered. Age is the age of the students taking the test (Apprentice: 1st and 2nd graders vs. Freshman: 3rd and 4th graders), contrast coded with Apprentice given a value of −1 and Freshman given a value of +1. Position on Test is the order of the word on the Spelling Test in the year it was administered, a number between 1 and 40, and is treated as a linear predictor. Year is the year of the test (2018-2021), treated as a random effect in our analysis. ID is the unique student ID number that students carry with them from year to year, treated as a random effect.

3.1.2 Contraction level variables

At the level of the contraction, three variables are considered. The first is Log Contraction Frequency, measured as the log of the count of how many times the contraction occurred across lemmas in a Unified English Braille version of the CELEX

Table 1 Zero-order correlation between fixed effects

Fixed effects	1	2	3	4	5	6	7	8	9	10	11
1. Age	1.0										
2. Position on Test	−0.01	1.0									
3. Log Contraction Freq	.13	−0.01	1.0								
4. Student Learning Order	.08	.05	−.27	1.0							
5. Teacher Learning Order	.14	.07	.08	.52	1.0						
6. Log Word Frequency	−.24	.05	.00	.03	−.05	1.0					
7. Number of Neighbors	−.32	.03	−.02	−.11	−.06	.06	1.0				
8. Log Odds Bicell Transition	.17	.03	.53	.07	.14	−.02	−.00	1.0			
9. Length	.38	−.07	.17	.11	.17	−.11	−.54	.24	1.0		
10. Word Position	−.21	−.01	−.22	.10	−.07	.03	.15	−.22	−.22	1.0	
11. Number of Contractions	.08	.14	.04	.05	.05	−.12	.00	.11	.06	0.01	1.0

database (see Fischer-Baum & Englebretson, 2016 for a description of this database). This value ranges from 2.24 for ⠱ 'WH' to 3.69 for ⠻ 'ER'. The second is Student Learning Order, based on the order in which contractions are introduced in the 1st and 2nd grade levels of *Building on Patterns* (Croft et al., 2009–2012), a widely-used braille-based curriculum for young braille learners in the United States and Canada.[2] In first and second grades combined, there are a total of 66 lessons in which contractions are introduced, reinforced, or practiced. The introduction of the one-cell contractions analyzed in our study range from the 1st lesson to the 47th lesson. The third variable is Teacher Learning Order, based on the 11 chapters of *Ashcroft's Programmed Instruction in Braille* (Holbrook & D'Andrea, 2014), a commonly-used textbook for braille courses in teacher preparation programs for TVIs. This variable is a number from 1-11, based on the chapter in which the contraction is introduced.[3] The order in which contractions are introduced in student curricula and teacher curricula is positively correlated (at .52, see Table 1, above), though relatively low variance inflation factors (VIF < 2) for each variable provide us some confidence that we can separately investigate the contribution of each one.

[2] We use the *Building on Patterns* curriculum as a proxy estimate of the order in which children are typically taught contractions. While this is the only commercially-available full curriculum for teaching braille, not all districts use it; for instance, some teachers prefer to create braille versions of the print-based reading curriculum used by sighted students in the general-education classroom. And young readers may of course also come across contractions in any order 'in the wild' as they read materials outside of class. This information is not available at the individual level for Braille Challenge participants, and so this variable must be understood as an approximation.

[3] As with Student Learning Order, this variable is also a proxy estimate, as teachers may have learned braille using other curricula. We chose this particular textbook because it is specifically designed for training TVIs, as compared with other programs that may be more geared toward transcribers, and it was the most frequently mentioned textbook in an informal survey of TVIs. Again, there is no information available at the level of individual teachers of the Braille Challenge participants about their teacher preparation programs or the way they learned braille, and so this variable must be understood as an approximation.

3.1.3 Word level variables

A larger set of lexical variables are also considered. Log Word Frequency is the log transform of the word frequency count taken from the English Lexicon Project (Balota et al., 2007) using the HAL database (Lund & Burgess, 1996). The HAL Lexicon was chosen since it contains an entry for "weren't", a critical item in our analysis since it includes a morpheme-bridging braille contraction, and other corpora for word frequency counts do not include it as an item. Number of Neighbors is calculated by counting the number of words in the Unified English Braille version of the CELEX database that differ from the target word by the substitution of a single cell. Log Odds Bicell Transitional Probability is the log of the odds that the cell preceding the contraction is followed by that contraction, again calculated from the braille version of the CELEX database. For example, ⠧ 'v' is frequently followed by the 'ER' contraction ⠻ (e.g., avERage, silvER) compared with other braille cells; while ⠉ 'c' is also followed by ⠻ 'ER' in some words (e.g., cERtaIN) it is more likely to be followed by other braille cells. Therefore, the bicell transitional probability is higher for the ER in avERage than for the ER in cERtaIN. Previous research in typing print English has shown that these transitional probabilities influence the motor planning of keypresses (e.g. Behmer & Crump, 2016). Therefore we opted for this measure rather than a more common measure like mean bigram frequency that reflects the transitional probabilities in the whole word and not just the specific contraction being produced. Length is the length of the contracted form in number of cells. In general, length tends to negatively correlate with word frequency. However, because the words in the Braille Challenge are selected specifically to be challenging for students, the correlation observed in our data set (−.11, see Table 1 above) is low enough to allow us to examine the independent contributions of length and frequency. Word Position is the position of the contraction within the word. For the sake of simplicity, position is contrast coded as being either the first or last cell of the word (+1), or a word-medial cell (−1), based on previous research demonstrating bow-shaped serial position functions in spelling accuracy (Wing & Baddeley, 2009). Finally, Number of Contractions is the total number of contractions (comprising both one-cell and multi-cell contractions) in the correct spelling of the word.

3.2 Participants

Participants include all students who took part in the Braille Challenge contest for any of the target years, have an available ID number, and are coded as at grade level. With these criteria, a total of 355 students took at least one of the seven spelling tests: for 236 we only have data from a single year, for 81 we have data from two years, for 30 we have data from three years, and for 7 we have data from all four possible years. Note that a full four-year data set is only possible for students who were at grade level in 1st grade in 2018 and participated in the 2018 Apprentice, 2019 Apprentice, 2020 Freshman, and 2021 Freshman contests. In contrast, students who were in 4th grade in 2018 could only possibly be included in one year, namely the 2018 Freshman contest.

3.3 Procedure

Data analysis was performed in R 4.1.3 (R Core Team, 2021) using the package lme4 (version 1.1-28, Bates et al., 2014) and the optimizer "bobyqa." We selected the subset of data in which the student's uncontracted spelling contained the constituent letters of the contraction. With this subset of data, we predicted whether or not the student would correctly produce the contraction in the contracted spelling using the following eleven fixed effects: Age, Position on Test, Log Contraction Frequency, Student Learning Order, Teacher Learning Order, Log Word Frequency, Number of Neighbors, Log Odds of Bicell Transition, Length, Word Position, Number of Contractions, as well as random effects of Year and Participant. Significance of each predictor was tested with a Wald test.

3.4 Results of Analysis 1: variables contributing to contraction use

Across the 212 contractions and the 355 participants, a total of 15,558 spelling trials were tabulated. The uncontracted spellings of 7,331 (47%) of these trials contain the letter sequence represented by the contraction. The remaining trials include no responses (18%), and a variety of other incorrect uncontracted spellings, including phonologically plausible errors (e.g., no GH in 'flight', because the student spelled it 'flite').

Analysis 1 focused on these 7,331 trials where the uncontracted spelling contained the letters of the target contraction, comprising responses from 347 participants. Of these, the contracted spelling of the word contains the correct contraction on 4,890 (67%) trials. The zero order correlations between the fixed effects entered into this model are reported in Table 1. The results of the model fit with the estimated weights of each variable in predicting correct contraction use are reported in Table 2. Variance inflation factor for all variables was less than 2, indicating no issues of multicollinearity in the analysis.

Among the task level variables, both Age and position on test are significant predictors of performance. Older students in the Freshman age group use contractions more accurately (3,776/5,198: 72%) than did younger students in the Apprentice age group (1,124/2,113: 53%). As students go farther into the 40-item spelling test, they are less likely to use contractions correctly. This is likely due to test fatigue, since words on the test are not designed to get more difficult as student's progress. (This is supported by a small positive correlation in Table 1 between position on test and word frequency, meaning that words towards the end of the spelling test are slightly higher in frequency.) Among the contraction level variables, there are significant effects of Contraction Frequency and Student Learning Order, with more frequent contractions being used more accurately, and contractions that are learned later in the *Building on Patterns* curriculum being used less accurately. Teacher Learning Order had no impact on contraction use in this task. Among the word level variables, there were significant effects of Word Position, Bicell Transition, and Word Frequency. Contractions that occur either as the first or the last cell in the word are used significantly more accurately than contractions that occur word medially. Contractions that are more predictable given the preceding cell are also more likely to

Table 2 Predictors of contraction use

Fixed effects	Estimate	SE	Pr(> |z|)
Intercept	0.515	0.588	0.381
Age	0.396	0.075	<.001
Position on List	−0.010	0.003	<.001
Log Contraction Freq	0.421	0.117	<.001
Student Learning Order	−0.018	0.004	<.001
Teacher Learning Order	−0.009	0.021	0.677
Log Word Frequency	0.044	0.020	0.030
Number of Neighbors	0.012	0.012	0.327
Log Odds Bicell Transition	0.915	0.097	<.001
Length	0.031	0.031	0.320
Word Position	0.383	0.038	<.001
Number of Contractions	0.033	0.055	0.549
Random Effects	Groups	SD	
Year	Intercept	0.188	
Participant	Intercept	2.334	

be used correctly. Contractions are more likely to be used correctly as word frequency increases. The other predictors – number of neighbors, length of the contracted spelling, number of contractions in the word – do not influence contraction use.

4 Analysis 2: contraction use and morphological bridging

After having determined the variables that influence overall contraction use as described in Sect. 3.4, we were then able to move on to the central question of our work and focus specifically on morpheme-bridging contractions. Analysis 2 seeks to establish whether participants are less likely to correctly use contractions when they bridge a morpheme boundary than when these same contractions occur tautomorphemically (inside of a single morpheme).

4.1 Procedure

We use a nested model comparison approach, with a model that includes a contrast-coded predictor of morpheme-bridging contraction (−1) versus tautomorphemic contraction (+1) contrasted with a baseline model that does not include this predictor.

As summarized above in Sect. 2.3, a total of five of the 280 words in the spelling subcorpus contain a morpheme-bridging contraction: ⠏⠗⠫⠊⠉⠰⠝ ‘prEDicTION’, two instances of ⠋⠗⠑⠫⠕⠍ ‘freEDom’ (once on the 2018 Freshman and once on the 2019 Apprentice contest), ⠺⠻⠢⠄⠞ ‘wER.EN’t’, and ⠍⠊⠌⠕⠕⠅ ‘miSTook’. These five words contain three distinct contractions that, in these cases, bridge morphemes (⠫ ‘ED’, ⠢ ‘EN’, and ⠌ ‘ST’) on four distinct tests (Apprentice 2018, Fresh-

Table 3 Parameter estimates in the bridging contraction model

Fixed Effects	Estimate	SE	Pr(> |z|)
Intercept	−0.713	0.670	0.287
Age	0.830	0.162	<.001
Position on List	−0.004	0.009	0.673
Log Word Frequency	0.172	0.060	0.004
Log Odds Bicell Transition	1.026	0.371	0.006
Morpheme Bridging	1.391	0.164	<.001
Random Effects	Groups	SD	
Participant	Intercept	1.885	
Contraction	Intercept	0.277	

man 2018, Apprentice 2019, and Freshman 2021). Our goal is to determine whether young spellers use these morpheme-bridging contractions less than when these same contractions occur tautomorphemically in other words on the Spelling contests, all else being equal. The relevant findings from Analysis 1 that contribute to Analysis 2 are strong effects of contraction level variables and of word position. Because of the nature of these results, we opted to compare these bridging contractions to a matched set of tautomorphemic contractions. Bridging contractions are by definition word medial, and due to the strong effects of word position on contraction use as observed in Sect. 3.4, we limited our analysis to tautomorphemic contractions that are also word medial. Because contraction level predictors strongly influenced contraction use, we limited our analysis to only words that included word medial ED, EN, and ST contractions, which allows us to remove contraction level predictors from the analysis, and treat contraction as a random effect. With these constraints, we identified a total of 24 tautomorphemic contractions for the analysis. When combined with the morpheme-bridging contractions, this analysis includes a total of 1,243 trials from 308 unique participants.

4.2 Results of Analysis 2: contraction use and morphological bridging

We ran a baseline model with the significant fixed effects from Analysis 1, excluding the contraction level predictors and word position which were controlled for by item selection. This baseline model included fixed effects of Age, Position on Test, Log Odds Bicell Transition and Log Word Frequency, and random effects of Participant and Contraction. Models that included random effects of Year resulted in a singular fit error, so it was removed from analysis. The baseline model was compared to the Bridging Contraction model, a nested model that included the same set of fixed and random effects and also contrast coded whether or not the contraction bridged morpheme boundaries. The log likelihood of the baseline model, with seven parameters, is −692.42, while the log likelihood of the Bridging Contraction model, with eight parameters, is −649.62. The model comparison strongly favors the Bridging Contraction model ($\chi^2(1) = 85.60$, $p < .001$). Table 3 reports the parameter estimates in the Bridging Contraction model.

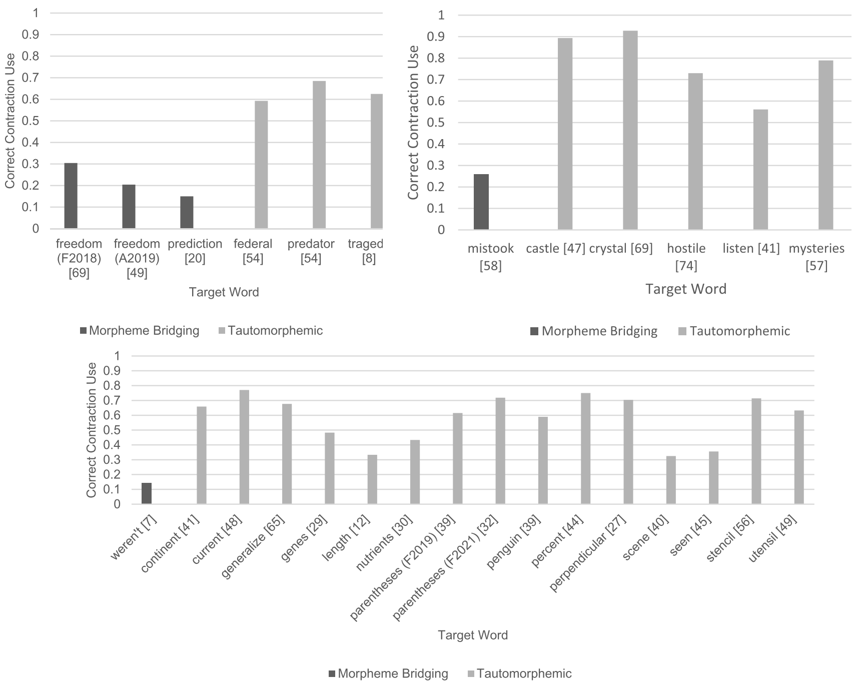

Fig. 1 Correct contraction use for each word in the analysis, divided by contraction (ED, ST and EN), with contractions that bridge morphemes shown in dark gray and contractions that are tautomorphemic shown in light gray. In brackets are the number of tokens included in the analysis for each word type

As the parameter estimates and the nested model comparison show, morpheme bridging has a significant impact on contraction use, with morpheme-bridging contractions being less likely to be used than those same contractions when occurring tautomorphemically in word medial positions, even when statistically controlling for other factors.

Indeed, the effect of morpheme bridging is striking, and clearly detectable even at the level of individual items. There are 1,040 trials with tautomorphemic contractions, of which the contracted spelling contains the contraction on 690 (66%) occasions. In contrast, there are 203 trials with bridging contractions, of which the contracted spelling only contains the contraction on 50 (25%) occasions. Figure 1 shows the results for each item, grouped by contraction. (A full text description of this figure, accessible to readers who are blind or visually impaired, appears in Appendix.)

As can be seen in this figure, all of the morpheme-bridging contractions are less likely to be used correctly than any of the tautomorphemic contractions. For the 5 morpheme-bridging items, the range of contraction use is 15% (the EN in wER.EN't) to 30% (the ED in freEDom, in the Freshman 2018 contest). For the 25 tautomorphemic contractions, the range of contraction use is 33% (the EN in scENe) to 93% (the ST in crySTal). These differences cannot be explained by other differences between the items in terms of variables that predict contraction use.

5 Discussion

The current study investigates how blind and visually-impaired elementary school students use contractions when writing braille, with a particular focus on the influence of morphological structure. We have shown that a variety of factors contribute to whether or not a student uses contractions correctly, and these factors are in line with what would be expected from the psycholinguistics literature. Older students (3rd and 4th grade) are more likely to use contractions correctly than younger students (1st and 2nd grade), which is consistent with existing research on a developmental trajectory of acquiring orthographic patterns when learning to spell (Treiman & Bourassa, 2000). Students' correct use of contractions declines for items appearing later on the spelling test, indicating some testing effects of fatigue or boredom. Students correctly use contractions at the beginnings and ends of words more often than in the middle of words, consistent with existing research on serial position effects in word spelling (e.g., Wing & Baddeley, 2009). Contraction use is sensitive to transitional probabilities. Specifically, contractions are used more correctly when their occurrence is more predictable given the immediately preceding cell. All else being equal, for example, the ER contraction is more likely to be used correctly in a word like avERage, because v is frequently followed by ER, compared to a word like cERtaIN, because c is followed by ER less often. These transitional probability effects are consistent with effects that have been reported in other typing tasks, for example, work showing effects of similar variables on the timing of keystrokes by expert typists of English print (Behmer & Crump, 2016). Taken together, it appears that blind and visually impaired students learn to use contractions following the same principles that sighted children learn the orthographic patterns for print.

We return now to the central focus of this study – the question of morphology and spelling. In words where orthography and morphology conflict in Unified English Braille, i.e. where a contraction is required to bridge a morpheme boundary, do young spellers primarily rely on orthographic rules at the expense of morphological regularity? Or, do they tend to violate these prescriptive orthographic rules and instead spell words to conserve morphological structure? In the Braille Challenge spelling contests in our corpus, evidence overwhelmingly points to the latter strategy: morphological structure tends to trump orthographic correctness. As discussed in Sect. 4.2 and shown in Fig. 1, above, students make significantly more errors in contraction use (i.e., they fail to use contractions as prescriptively required) in the five words in the corpus where a contraction bridges a morpheme boundary than they do in words where that same contraction occurs tautomorphemically. In the 203 trials with bridging-contractions, only 50 (25%) of the word tokens contain correct contraction use. On the other hand, in the 1,040 trials where those same contractions occur tautomorphemically, 690 (66%) of the tokens are correct. To put it another way, a student is significantly more likely to get an item wrong on a Braille Challenge spelling contest when it is a morphologically-bridged word than when that same contraction occurs in a non-bridged environment. Stem conservation takes precedence over orthographic rules, and students avoid using contractions that bridge morphology, even when this leads to incorrect answers on the spelling tests. The effect of morphological bridging on contraction use is well beyond the effects of the general variables shown in Sect. 3.4 that correlate with the overall use of contractions.

These findings raise several questions for consideration and potential follow-up. First, what might the findings contribute to braille research, development, and pedagogy? Second, what might the findings contribute to our understanding of the nature of orthographic morphemes, and to the place of braille in the reading sciences more broadly? We take up these issues in the following subsections.

5.1 Implications for braille research

Morphology matters in English braille. The current findings clearly demonstrate that young braille spellers take morphological structure into account when writing words for the Braille Challenge spelling contests. The findings of Fischer-Baum and Englebretson (2016) likewise demonstrate that proficient adult braille readers take morphology into account when reading words in a lexical decision task. Both of these studies provide strong evidence that morphological structure plays a role in braille reading and writing, and this opens up numerous questions for further research. For instance, as of yet, there has been no systematic study of morphological awareness in the oral language of young braille learners and the extent to which this correlates with literacy achievement. The interaction of contractions and sublexical structure (in terms of digraphs, syllables, and morphemes) in the writing of older students (such as in the Speed and Accuracy contests of the Braille Challenge), and in the spontaneous writing of proficient adult English braille users would also be fruitful areas of research. Finally, sublexical structure in braille across a diverse sample of the world's languages is wide open for investigation.

Regarding this last point, it is crucial to not overgeneralize the findings of our current work to braille in other languages, since the current study examines only English braille. There may indeed be important questions regarding which aspects of braille, if any, are domain general for tactile reading. But, just as with print research, we must study the specifics of a writing system on its own terms within a specific language, and not assume, say, that what is true for English is true cross-linguistically. Researchers must remember that there is no such thing as "braille" or "the braille code" independent of a particular language. The grapheme-to-phoneme correspondences, syllable structures, morphology, word length, and orthographic depth across languages in braille reading and writing parallel the variability across languages in print reading and writing—often with the added variable of contractions, which are also language specific.

Another area in need of further research is the relationship between the two orthographies of English braille. As described in Sect. 2.3, our analysis takes the uncontracted spelling as a baseline to determine rates of contraction use across all words in our corpus. However, this methodological decision should not be taken as a claim about the mental representations of word forms for braille users themselves. There is no evidence that proficient braille writers start with the uncontracted spelling and apply a series of encoding rules to arrive at the contracted form, nor that proficient braille readers first 'decode' a contracted form into uncontracted spelling before recognizing the word.[4] The few studies that have been done on this question, in fact,

[4] This may, however, be a strategy that sighted teachers use when they read and write braille, and that former print readers use when learning it.

show the opposite—that proficient braille readers likely have distinct mental representations for contracted versus uncontracted braille, and do not automatically transpose from one system to another. Millar (1997, pp. 185-189) conducted a matching experiment in which braille readers aged 11-19 were asked to judge whether pairs of words are the same or different. The relevant word pairs on the lists consisted of a word in its contracted form, followed by the same word written in uncontracted braille. Millar measured the scanning latencies of fingers as subjects read each word in the pair to make their judgement, hypothesizing that faster scanning speeds per character correlate with faster processing. Millar found that this task was relatively slow and difficult for all readers compared to comprehension experiments, and performance was influenced both by word frequency and by a reader's former experience with print. Former print readers who had recently begun to learn braille showed no differences by word frequency and were marginally faster reading uncontracted braille. On the other hand, experienced braille readers read the contracted forms of high-frequency words faster than the corresponding uncontracted forms, but took longer with low-frequency words. In sum, "it was clear, therefore, that these young students were perfectly able to translate contractions into full spelling. But the latencies showed that the translations were by no means automatic" (Millar, 1997, p. 186). Wells-Jensen et al. (2007) likewise provide evidence that when writing braille, contractions are stored as part of the mental representation of a word, rather than automatically translated from uncontracted braille by a set of rules imposed on a serially ordered string of letters. The consequences of learning two orthographies for the same writing system, such as contracted and uncontracted braille, is an area in need of research. As Millar (1997, p. 189) observed over a quarter century ago: "A good deal more work is needed before we understand the relation between the mental representations of the contracted and the full orthography of words". But it is clear at least that models that assume users 'encode' or 'decode' between orthographies are not supported by the existing evidence.

5.2 Implications for braille development

Our findings clearly demonstrate that, when the rules of English braille orthography come into conflict with morphological structure, young braille spellers tend to follow the morphology, and this leads to errors in braille usage. The findings of Fischer-Baum and Englebretson (2016) demonstrate that bridged morphology affects proficient adult readers as well. While morphological bridging only applies to a small number of words overall—e.g., only 5 of the 280 items in the Braille Challenge spelling contests in our corpus contain a contraction that bridges a morpheme boundary—the evidence is clear that words with bridged morphology pose difficulties for both young learners and for proficient adult readers. Unlike most writing systems, Unified English Braille is directly overseen and regulated by a standards-setting body, the International Council on English Braille (ICEB), which means that the writing system is malleable. Theoretically, it would be relatively straightforward for ICEB to remove these hurdles, simply by updating the Rulebook (Simpson, 2013) so as to disallow contractions that would cross morpheme boundaries in morphologically complex words. Exactly how the rules of Unified English Braille came to be the way they are is a complicated story that lies well outside the scope of the current article. As noted in Sect. 1, the Rulebook already contains specific prohibitions against using contractions that would bridge the stems of compound words: "Do not use a groupsign which would bridge the words which make up an unhyphenated compound word" (Simpson, 2013, p. 146). E.g., ⠹ 'TH' is disallowed in compounds such as 'boathouse', 'anthill', 'foothold', etc. There is already overt recognition in the Rulebook that morphology matters; but beyond compound words, this recognition is sporadic and inconsistent at best. We hope that our ongoing work will enable an evidence-based reconsideration to further extend the prohibition on contractions so as to conserve the stems in morphologically-complex words. Standards-setting bodies tend to proceed slowly and deliberately, rightfully seeking to avoid unexpected negative consequences for users. But we hope that we may begin to see incremental changes in this area as evidence continues to mount that braille readers rely on sublexical structure in many of the same ways that print readers do.

5.3 Implications for braille pedagogy

There has been little focus on morphology as applied to the teaching of braille. There has also been scant communication between those who train TVIs and researchers in the cognitive and reading sciences who work on morphology in literacy. Publications on braille pedagogy for TVIs (e.g., Swenson, 2016) are typically based on well-established educational research sources for print reading, such as the National Reading Panel (2000). However, since National Reading Panel (2000) does not explicitly include morphology in its areas of reading instruction, braille professionals may have the impression that morphology is inconsequential, since it is not overtly mentioned alongside areas such as phonemic awareness and phonics. We hope that our ongoing work will begin to change this perception. As the role of sublexical structure in braille reading and writing becomes clearer, pedagogical materials could be developed to leverage the learner's implicit knowledge of morphology, and to integrate braille contractions into the learner's developing orthographic knowledge. The *Building on Patterns* curriculum (Croft et al., 2009–2012) already focuses on structured ways of teaching contractions, and incorporating morphological structure into the curriculum would be a logical next step. In any case, our findings clearly show that reading and writing braille is not simply a matter of 'coding' and 'decoding' contractions independent of other linguistic factors. If it were, then contractions that cross morpheme boundaries would not show differences in usage accuracy from these same contractions occurring tautomorphemically. These findings suggest that braille should not primarily be taught as a "code" to represent print, but rather as a writing system with its own unique structural characteristics (cf. Englebretson et al., 2023; Hamp & Caton, 1984), which enables literacy for students who are blind or visually impaired in the same ways that print enables literacy for students who are sighted.

The results of Analysis 1, which sought to establish the primary task-level, contraction-level, and word-level variables that contribute to whether a young braille speller uses a contraction or not, may be useful for curriculum development. Our findings, for example, that contractions that occur in the middle of a word are used significantly less accurately than those that occur either as the first or the last cell in the word suggest that students may benefit from focused teaching and practice with words that contain word-medial contractions. In addition, while it is certainly not surprising that students show greater accuracy with contractions that they learned earlier rather than later, the findings support the efficacy of introducing students to as many contractions as early as possible so as to maximize opportunities to read and write them. (cf. Wall Emerson et al., 2009, for additional evidence regarding the correlation between early contraction learning and more successful acquisition of literacy skills).

The findings of Analysis 2, namely that young braille spellers have difficulty with correct use of contractions when they bridge morpheme boundaries, also have potential implications for pedagogy. As noted in Sect. 1, morphological bridging is neither phonologically grounded nor morphologically motivated. Rather, it emerges whenever the letters comprising a contraction happen to cross a morpheme boundary, since current rules of contraction usage do not proscribe against this—except at stem boundaries in compound words. Bridged words form no type of natural class, and morpheme bridging appears to serve no function in facilitating reading or writing, other than attempting to keep the prescriptive rules of braille contractions as general and regular as possible. As our work has demonstrated, morphological knowledge tends to trump the regular rules of contraction use. Readers take longer to recognize words with bridged morphology and do so with more errors (Fischer-Baum & Englebretson, 2016). And as the present study shows, young braille spellers make significantly more errors on bridging contractions than they do when those same contractions occur tautomorphemically. If one of the goals of braille literacy acquisition is for students to learn to use contractions as prescriptively required, then as long as morphological bridging remains part of Unified English Braille, learners will need to override the effects of their implicit knowledge of morphology in these contexts and learn them as irregular forms. As of yet, no studies have been conducted as to the best way to achieve this. There are numerous studies with print learners demonstrating that teaching morphological patterns leads to improvement in reading and spelling (for reviews, see Bowers et al., 2010; Carlisle et al., 2010; Goodwin & Ahn, 2013). These studies tend to focus on stem conservation. The case of bridged morphology in braille, however, may best be thought of as stem de-conservation. For example, in morphologically-bridged words like ⠋⠗⠑⠫⠕⠍ ‘freeEDom’ or ⠍⠊⠌⠕⠕⠅ ‘miSTook’, the stems ‘free’ and ‘took’ are simply not present orthographically since they have been merged with the affix, and so readers cannot recognize them at all in these derived forms. (In fact, there is nothing about the structure of the contracted forms that would cue a reader that they are morphologically complex words.) It is an open question as to whether, or to what degree, explicit teaching of morphologically-bridged words would enable braille learners to override morphological structure and learn them as irregular forms, so as to correctly use contractions across morpheme boundaries, although effects of age/reading experience and word frequency will no doubt contribute to this as well. It is also an open question as to why it would be desirable to devote scarce teaching resources to this issue in the first place, aside from enabling students to adhere to the prescriptive standards for braille contraction use. For the young spellers in our corpus at least, failing to meet these standards does have consequences, in that those who do not use morphological bridging perform less well on the Braille Challenge contests, which may cost them in terms of prestige and prizes. The role of prescriptivism, tightly-regulated language ideologies, and standardization in braille is an important question, but such sociolinguistic questions (which arise for print spellers as well), lie outside the scope of the current paper.

5.4 Implications for the reading sciences

Our findings contribute to the reading sciences in at least three ways. First, as with Fischer-Baum and Englebretson (2016), we have confirmed that tactile readers are sensitive to sublexical structure, and that morphology matters for users of English braille. These findings should call for a reconsideration, or at least a more careful operationalization, of definitions that have tended to consider the recognition of orthographic morphemes solely in visual terms, e.g., "the visual identity of meaningful word parts" (Venezky, 1999, p. 9). Certainly, the overwhelming majority of people do read visually, and the vast majority of reading research likewise focuses on print. But research on braille provides clear evidence that recognition of morphemes is not strictly based in the visual system. Broader awareness of braille, and inclusion of braille in models of reading, will sharpen our theories of reading and clarify the role of modality in the reading process. Braille is part of the immense diversity in the world's writing systems, and we believe it has much to offer the reading sciences in contributing to understanding the nature of perception, cognition, and the diverse methods humans have at their fingertips (or their eyes) for interacting with written language (cf. Englebretson et al., 2023).

The fact that morphology matters for the reading and writing of both braille and print does not imply that it works in exactly the same ways in both modalities. The affordances of the tactile system differ from those of the visual system, and a variety of questions have yet to be asked about the nature of orthographic morphemes in braille and how they are processed. For example, there has been considerable research on the early and unconscious recognition of morphemes in print reading (e.g., Rastle et al., 2004; Rastle & Davis, 2008). We do not yet know whether any of these effects hold true for braille readers, and, given the way braille is read through active scanning by the fingers rather than fixation by the eye, some instrumentation and methodologies common in research with print readers are not viable in research with braille readers. Braille research is a relatively new field, for which relevant research instruments and experimental methods have yet to be developed. The detection and processing of morphemes in braille reading remains a wide-open question for future research.

Our research also contributes to reading science by providing additional evidence that young elementary-school-age children (grades 1-4) are sensitive to morphology. Our work dovetails with previous investigations of the developmental trajectory of morpho-orthographic processing in several languages (e.g., Beyersmann et al., 2012, 2019, 2021) and is the first to address this question in a nonvisual writing system. While our current study cannot speak directly to a developmental trajectory, our findings clearly show that braille-reading children in grades 1-4 must rely to some degree on morphological knowledge to determine the use or non-use of contractions. If these children were not sensitive to morphological structure, then we would not expect to find the significant differences in contraction use across bridged and non-bridged contexts that are so clearly evident in our data.

5.5 Future directions and conclusion

There are several limitations in the current study that future work could address. First, as operationalized in Sect. 2.3, this study only deals with one-cell contractions. Future researchers may wish to widen the scope and investigate the factors that lead to the use of multi-cell contractions and the degree to which these correspond to the findings in Sect. 3.4. Second, as we had no control over the words on the spelling contests, our work is broadly descriptive in nature. As in other corpus studies, the items are not carefully balanced. Future experimental studies should be designed to examine the interaction between braille contractions and morphology with more precision and specificity. Third, new instrumentation to measure the timing of keypresses during braille writing would provide additional details of production aside from whether contractions are used correctly. Such measures have provided novel insights into the influence of linguistic structure on writing for print readers and writers (Gagné & Spalding, 2016; Pinet et al., 2016), and likely would benefit our understanding of braille as well. Fourth, future work on reading and writing braille in naturalistic contexts outside of the laboratory or the spelling test may shed light on aspects of bridging not captured here. Finally, the focus of our current article is on morphology; but braille contractions can obscure linguistic structure in other ways too, such as bridging syllable boundaries and disrupting digraphs. The interplay between braille contractions and other types of sublexical structures would be a fruitful area for future research. We plan to address some of these questions soon, using the Braille Challenge Research Corpus and experimental data collected from proficient adult braille users.

In sum, Unified English Braille provides an interesting case study of a writing system in which orthographic rules flout morphological structure, as some braille contractions prescriptively bridge morpheme boundaries. Our findings demonstrate that the use or non-use of contractions is influenced by higher-level linguistic representations which supersede the prescribed rules of contraction use. Young braille spellers' morphological knowledge tends to take precedence over prescriptive orthographic rules, demonstrating that the role of morphology is indeed a powerful influence on spelling.

Full-text description of Fig. 1, accessible to readers who are blind or visually impaired

Figure 1 shows three plots, each with an x-axis labeled by individual words and a y-axis ranging from 0 to 1 with lines every .1. Each plot is a bar graph, with the length of the bar reflecting the "correct contraction use" proportion. The words that have bridging contractions appear in dark gray, and the words with identical tautomorphemic contractions appear in light gray. The number in the brackets after the label indicates the number of tokens included in the analysis for each word type.

The upper left plot shows the ED contraction occurring in 6 words, 3 bridging and 3 tautomorphemic. The values are as follows:

Morpheme Bridging	
freedom (F2018) [69]	0.304
freedom (A2019) [49]	0.204
prediction [20]	0.150
Tautomorphemic	
federal [54]	0.593
predator [54]	0.685
tragedy [8]	0.625

The upper right plot shows the ST contraction occurring in 7 words, 1 bridging and 6 tautomorphemic. The values are as follows:

Morpheme Bridging	
mistook [58]	0.259
Tautomorphemic	
castle [47]	0.894
crystal [69]	0.928
hostile [74]	0.730
listen [41]	0.561
mysteries [57]	0.789
pasture [40]	0.675

The third plot shows the EN contraction occurring in 16 words, 1 bridging and 15 tautomorphemic. The values are as follows:

Morpheme Bridging	
weren't [7]	0.143
Tautomorphemic	
continent [41]	0.659
current [48]	0.771
generalize [65]	0.677
genes [29]	0.483
length [12]	0.333
nutrients [30]	0.433
parentheses (F2019) [39]	0.615
parentheses (F2021) [32]	0.719
penguin [39]	0.590
percent [44]	0.759
perpendicular [27]	0.704
scene [40]	0.325
seen [45]	0.356
stencil [56]	0.714
utensil [49]	0.633

Acknowledgements We gratefully acknowledge the Braille Institute of America for recognizing the potential of our research and for granting us access to the Braille Challenge contests; our work would not have been possible without their partnership. For logistical support in preparing the Braille Challenge hardcopy data for digitization, we wish to thank Sophie Armstrong and Allana Pierce, Graduate Research Assistants at the University of British Columbia. And we would like to express our deepest gratitude to Charmaine Co for the data entry; the Braille Challenge Research Corpus would not be possible without her sensitive fingers, attention to detail, and strong work ethic.

Author Contribution All authors collaboratively planned the research questions and shaped the analyses. Rebecca Treiman proposed Analysis 1. Cay Holbrook coordinated the logistics of the hardcopy Braille Challenge data and supervised its digitization. Robert Englebretson and Cay Holbrook coded the braille contractions. Simon Fischer-Baum analyzed the data, drafted the manuscript sections related to Analyses 1 and 2, and prepared all tables and figures. Robert Englebretson wrote the manuscript aside from Fischer-Baum's sections. All authors closely edited and commented on the manuscript.

Funding The research reported here was supported by the Institute of Education Sciences, U.S. Department of Education, through Grant R324A190093 to Rice University. The opinions expressed are those of the authors and do not represent views of the Institute or the U.S. Department of Education. This work is also supported by the Independent Research and Development Program while S.F-B was serving at the National Science Foundation.

Declarations

IRB Approval Work with human subjects related to this project has been reviewed and approved by the Rice University and University of British Columbia Institutional Review Boards: Rice IRB-FY2019-298; UBC H19-02491.

Competing Interests The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Baayen, R. H., Piepenbrock, R., & Van Rijn, H. (1993). *The CELEX lexical database*. Philadelphia: Linguistic Data Consortium. [CD-ROM]

Bahr, R. H., Silliman, E. R., & Berninger, V. W. (2020). Derivational morphology bridges phonology and orthography: Insights into the development of word-specific spellings by superior, average, and poor spellers. *Language, Speech, & Hearing Services in Schools*, *51*(3), 640–654. https://doi.org/10.1044/2020_LSHSS-19-00090.

Balota, D. A., Yap, M. J., Hutchison, K. A., Cortese, M. J., Kessler, B., Loftis, B., Neely, J. H., Nelson, D. L., Simpson, G. B., & Treiman, R. (2007). The English lexicon project. *Behavior Research Methods*, *39*(3), 445–459. https://doi.org/10.3758/BF03193014.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. ArXiv preprint. arXiv:1406.5823.

Behmer, L. P. Jr., & Crump, M. J. C. (2016). Crunching big data with fingertips: How typists tune their performance toward the statistics of natural language. In M. N. Jones (Ed.), *Big data in cognitive science* (pp. 329–345). New York: Psychology Press. https://doi.org/10.4324/9781315413570.

Beyersmann, E., Castles, A., & Coltheart, M. (2012). Morphological processing during visual word recognition in developing readers: Evidence from masked priming. *Quarterly Journal of Experimental Psychology*, *65*(7), 1306–1326. https://doi.org/10.1080/17470218.2012.656661.

Beyersmann, E., Grainger, J., & Castles, A. (2019). Embedded stems as a bootstrapping mechanism for morphological parsing during reading development. *Journal of Experimental Child Psychology*, *182*, 196–210. https://doi.org/10.1016/j.jecp.2019.01.010.

Beyersmann, E., Mousikou, P., Schroeder, S., Javourey-Drevet, L., Ziegler, J. C., & Grainger, J. (2021). The dynamics of morphological processing in developing readers: A cross-linguistic masked priming study. *Journal of Experimental Child Psychology*, *208*, 105–140. https://doi.org/10.1016/j.jecp.2021.105140.

Bowers, P. N., Kirby, J. R., & Deacon, S. H. (2010). The effects of morphological instruction on literacy skills: A systematic review of the literature. *Review of Educational Research*, *80*(2), 144–179. https://doi.org/10.3102/0034654309359353.

Bryant, P., Nunes, T., Pretzlik, U., Bell, D., Evans, D., & Olsson, J. (2006). From the laboratory to the classroom. In T. Nunes & P. Bryant (Eds.), *Improving literacy by teaching morphemes* (pp. 65–103) London: Routledge. https://doi.org/10.4324/9780203969557.

Burton, L., Nunes, T., & Evangelou, M. (2021). Do children use logic to spell logician? Implicit versus explicit teaching of morphological spelling rules. *British Journal of Educational Psychology*, *91*(4), 1231–1248. https://doi.org/10.1111/bjep.12414.

Carlisle, J. F. (1988). Knowledge of derivational morphology and spelling ability in fourth, sixth, and eighth graders. *Applied Psycholinguistics*, *9*(3), 247–266. https://doi.org/10.1017/S0142716400007839.

Carlisle, J. F. (1995). Morphological awareness and early reading achievement. In L. B. Feldman (Ed.), *Morphological aspects of language processing* (pp. 189–209). New York: Lawrence Erlbaum. https://doi.org/10.4324/9780203773291.

Carlisle, J. F. (2000). Awareness of the structure and meaning of morphologically complex words: Impact on reading. *Reading and Writing*, *12*, 169–190. https://doi.org/10.1023/A:1008131926604.

Carlisle, J. F. (2003). Morphology matters in learning to read: A commentary. *Reading Psychology*, *24*(3–4), 291–322. https://doi.org/10.1080/02702710390227369.

Carlisle, J. F., McBride-Chang, C., Nagy, W., & Nunes, T. (2010). Effects of instruction in morphological awareness on literacy achievement: An integrative review. *Reading Research Quarterly*, *45*(4), 464–487. https://doi.org/10.1598/RRQ.45.4.5.

Chliounaki, K. (2007). Morphological awareness and literacy skills: A review. *Psychology: The Journal of the Hellenic Psychological Society*, *14*(3), 250–275. https://doi.org/10.12681/psy_hps.23865.

Croft, J., Dilworth, K., Truan, M., Ward, M., Wingell, R., Pester, E., & Boley, C. (2009–2012). *Building on patterns: The primary braille literacy program: First grade and second grade*. Louisville: American Printing House for the Blind.

Englebretson, R., Holbrook, M. C., & Fischer-Baum, S. (2023). A position paper on researching braille in the cognitive sciences: De-centering the sighted norm. *Journal of Applied Psycholinguistics*, *44*(3), 400–415. https://doi.org/10.1017/S0142716423000061.

Fischer-Baum, S., & Englebretson, R. (2016). Orthographic units in the absence of visual processing: Evidence from sublexical structure in braille. *Cognition*, *153*, 161–174. https://doi.org/10.1016/j.cognition.2016.03.021.

Gagné, C. L., & Spalding, T. L. (2016). Effects of morphology and semantic transparency on typing latencies in English compound and pseudocompound words. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *42*(9), 1489–1495. https://doi.org/10.1037/xlm0000258.

Goodwin, A. P., & Ahn, S. (2013). A meta-analysis of morphological interventions in English: Effects on literacy outcomes for school-age children. *Scientific Studies of Reading*, *17*(4), 257–285. https://doi.org/10.1080/10888438.2012.689791.

Hamp, E. P., & Caton, H. (1984). A fresh look at the sign system of the braille code. *Journal of Visual Impairment & Blindness*, *78*(5), 210–214. https://doi.org/10.1177/0145482X8407800506.

Holbrook, M. C., & D'Andrea, F. M. (2014). *Ashcroft's programmed instruction in Unified English Braille*. Germantown: SCALARS Publishing.

Kemper, M. J., Verhoeven, L., & Bosman, A. M. T. (2012). Implicit and explicit instruction of spelling rules. *Learning and Individual Differences*, *22*(6), 639–649. https://doi.org/10.1016/j.lindif.2012.06.008.

Kessler, B., & Treiman, R. (2015). Writing systems: Their properties and implications for reading. In A. Pollatsek & R. Treiman (Eds.), *Oxford handbook of reading* (pp. 10–25). London: Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199324576.013.1.

Lauenstein, C. (2007). On the compatibility of the braille code and universal grammar. Unpublished Ph.D. Dissertation, Institute of English Linguistics, Universität Stuttgart, Stuttgart, Germany.

Lund, K., & Burgess, C. (1996). Producing high-dimensional semantic spaces from lexical co-occurrence. *Behavior Research Methods, Instruments, and Computers*, *28*(2), 203–208. https://doi.org/10.3758/BF03204766.

Millar, S. (1997). *Reading by touch*. London: Routledge.
Nagy, W. E., Carlisle, J. F., & Goodwin, A. P. (2014). Morphological knowledge and literacy acquisition. *Journal of Learning Disabilities*, *47*(1), 3–12. https://doi.org/10.1177/0022219413509967.
National Reading Panel (2000). Teaching children to read: An evidence-based assessment of the scientific research literature on reading and its implications for reading instruction. (NIH Publication No. 00-4769). National Institute of Child Health and Development. https://www1.nichd.nih.gov/publications/pubs/nrp/Documents/report.pdf.
Pinet, S., Ziegler, J. C., & Alario, F.-X. (2016). Typing is writing: Linguistic properties modulate typing execution. *Psychonomic Bulletin and Review*, *23*(6), 1898–1906. https://doi.org/10.3758/s13423-016-1044-3.
R Core Team (2021). *R: A language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing. https://www.R-project.org/.
Rastle, K. (2019). The place of morphology in learning to read in English. *Cortex: A Journal Devoted to the Study of the Nervous System and Behavior*, *116*, 45–54. https://doi.org/10.1016/j.cortex.2018.02.008.
Rastle, K., & Davis, M. H. (2008). Morphological decomposition based on the analysis of orthography. *Language and Cognitive Processes*, *23*(7–8), 942–971. https://doi.org/10.1080/01690960802069730.
Rastle, K., Davis, M. H., Marslen-Wilson, W. D., & Tyler, L. K. (2000). Morphological and semantic effects in visual word recognition: A time-course study. *Language and Cognitive Processes*, *15*(4–5), 507–537. https://doi.org/10.1080/01690960050119689.
Rastle, K., Davis, M. H., & New, B. (2004). The broth in my brother's brothel: Morpho-orthographic segmentation in visual word recognition. *Psychonomic Bulletin and Review*, *11*, 1090–1098. https://doi.org/10.3758/bf03196742.
Rubin, H. (1988). Morphological knowledge and early writing ability. *Language and Speech*, *31*(4), 337–355. https://doi.org/10.1177/002383098803100403.
Sandra, D. (2022). Too little morphology can kill you: The interplay between low-frequency morpho-orthographic rules and high-frequency verb homophones in spelling errors. In R. Levie, A. Bar-On, O. Ashkenazi, E. Dattner, & G. Brandes (Eds.), *Literacy studies: Vol. 23. Developing language and literacy* (pp. 191–229). Cham: Springer. https://doi.org/10.1007/978-3-030-99891-2_8.
Sheffield, R. M., D'Andrea, F. M., Morash, V., & Chatfield, S. (2022). How many braille readers?: Policy, politics, and perception. *Journal of Visual Impairment & Blindness*, *116*(1), 14–25. https://doi.org/10.1177/0145482X211071125.
Simpson, C. (Ed.) (2013). *The rules of Unified English Braille* (2nd ed.). Round Table on Information Access for People with Print Disabilities Inc. and International Council on English Braille. http://www.iceb.org/Rules%20of%20Unified%20English%20Braille%202013.pdf.
Swenson, A. M. (2016). *Beginning with braille: Firsthand experiences with a balanced approach to literacy* (2nd ed.). American Foundation for the Blind.
Treiman, R., & Bourassa, D. C. (2000). The development of spelling skill. *Topics in Language Disorders*, *20*(3), 1–18. https://doi.org/10.1097/00011363-200020030-00004.
Treiman, R., & Cassar, M. (1996). Effects of morphology on children's spelling of final consonant clusters. *Journal of Experimental Child Psychology*, *63*(1), 141–170. https://doi.org/10.1006/jecp.1996.0045.
Venezky, R. L. (1999). *The American way of spelling: The structure and origins of American English orthography*. New York: The Guildford Press.
Wall Emerson, R. S., Holbrook, M. C., & D'Andrea, F. M. (2009). Acquisition of literacy skills by young children who are blind: Results from the ABC braille study. *Journal of Visual Impairment & Blindness*, *103*(10), 610–624. https://doi.org/10.1177/0145482X0910301005.
Wells-Jensen, S., Schwartz, A., & Gosche, B. (2007). A cognitive approach to brailling errors. *Journal of Visual Impairment & Blindness*, *101*(7), 416–428. https://doi.org/10.1177/0145482X0710100704.
Wing, A. M., & Baddeley, A. D. (2009). Righting errors in writing errors: The Wing and Baddeley (1980) spelling error corpus revisited. *Cognitive Neuropsychology*, *26*(2), 223–226. https://doi.org/10.1080/02643290902823612.
Wright, T. (2010). Looking for power: The difficulties and possibilities of finding participants for braille research. *Journal of Visual Impairment & Blindness*, *104*(12), 775–780. https://doi.org/10.1177/0145482X1010401206.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.