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THEORETICAL/REVIEW

# Co-activation of phonological and orthographic codes in various modalities of language processing: A systematic and meta-analytic review

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## Abstract

A vast amount of research has been dedicated to clarifying whether spoken word processing (listening) or production (speaking) is constrained by orthographic codes, and whether written word processing (reading) or production (writing) is constrained by phonological codes. Little work has explored what factors might modulate such cross-modality effects. In this paper, we first provided a comprehensive review of existing evidence, then conducted four meta-analyses to determine the size of cross-modality effects, and we explored potential factors that might modulate these effects. We identified robust orthographic effects on spoken word recognition ($k = 93$, corrected $d = 0.61$) and production ($k = 34$, corrected $d = 0.44$), and robust phonological effects on written word recognition ($k = 178$, corrected $d = 0.49$) and production ($k = 28$, corrected $d = 0.35$). Moderator analyses indicated that cross-modality effects may be modulated by the tasks used and by language nativeness of participants. These results shed light on our understanding of language processing.


**Keywords** Co-activation · Orthographic effect · Phonological effect · Meta-analysis

## Introduction

Language processing involves computations and manipulations of various cognitive representational systems including semantics, phonology and orthography. Over the last 40 years or so, the issue of how these various subsystems interact in a given language task and domain has been one of the dominating themes. A substantial amount of research has been dedicated to exploring 'cross-modality' effects in lexical access and language more broadly, i.e., is spoken word recognition or production constrained by orthographic codes, and is written word recognition or production constrained by phonological codes? However, little work has examined what factors might modulate these effects. Hence, despite the substantial number of empirical studies exploring the co-activation of sound and spelling in the last decades, a complete picture is still lacking. In the work reported here, we first provide a comprehensive theoretical review of the existing evidence on the contribution of orthography to spoken word recognition and production, and the contribution of phonology to written word recognition and production. Second, we conducted four corresponding meta-analyses to assess the magnitude of cross-modality effects for each of these modalities separately. Third, we conducted meta-regressions to explore potential modulators which might influence the cross-modality effect. Because our review and meta-analyses specifically explore cross-modality effects in the various modalities (listening, speaking, reading, writing) we do not consider tasks which by their nature require cross-modal processing. For instance, reading aloud requires retrieval of phonology and so does not constitute an adequate test case of whether reading as such involves cross-modal activation of phonological representations. Similarly, writing-to-dictation or spelling involves conversion of sound into orthography, and therefore is not informative whether writing implicates activation of phonological codes.

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Exploration of cross-modality effects of the type we are interested in is theoretically informative because they reflect a fundamental property of how the human language system works. Specifically, presence of a cross-modality effect in a given domain would argue against a strictly modular and hierarchical organization of linguistic representations (Fodor, 1983). If it were to be the case that orthographic and phonological representations engage in cross-talk whenever one of these codes is accessed, the most obvious explanation would involve an 'online' account according to which orthography and phonology are bidirectionally connected in the mind/brain. Hence, orthographic codes are automatically activated whenever phonological codes are accessed and vice versa (e.g., Ziegler & Ferrand, 1998). Online co-activation could potentially account for all four types of cross-modality effects but specifically, such co-activation would fall naturally out of models of reading/writing in which spelling and sound are typically closely intertwined (e.g., Damian, 2019; Frost & Ziegler, 2007; Penke & Schrader, 2008).

An alternative explanation has been proposed specifically to account for orthographic effects in phonologically based tasks. According to an 'offline restructuring' account, it is the acquisition of literacy which restructures preexisting phonological representations, leading to 'phonographic' representations that integrate orthographic knowledge into spoken codes (Pattamadilok et al., 2010). This type of restructuring could potentially account for orthographic effects on spoken word recognition (e.g., Perre et al., 2009a, b) and production (e.g., Rastle et al., 2011), without the need to assume online cross-activation of sound and spelling. It is also possible that in phonologically based tasks, both accounts hold simultaneously (e.g., phonological representations are restructured via literacy, and orthographic codes are cross-activated when engaging in phonological processing; e.g., Dehaene et al., 2010). The primary aim of the current article was to establish and quantify the various types of cross-modality effects at the behavioural level; however, the issue of 'online' versus 'offline' accounts of cross-modal activation is unlikely to be resolvable with behavioural evidence alone, and neuroscientific studies will have particular relevance. In the *Discussion* section we will expand on this issue in greater detail.

## Theoretical review

### Orthographic effects on spoken word recognition

Literacy may change the way people process speech information (e.g., Frith, 1998). Evidence for the orthographic influence on auditory spoken word processing comes from comparisons between illiterate and literate individuals. Research has demonstrated that learning to read can profoundly alter the cortical network for language (Dehaene et al., 2010). Literacy enhances phonological activation in response to speech in the planum temporale and enables top-down activation of orthographic representations from spoken input (Dehaene et al., 2010). In addition, a substantial amount of research has been conducted to explore whether, for literate individuals, spoken word processing is affected by orthographic properties. Investigations on the contribution of orthography to spoken word processing often manipulate orthographic properties and examine how the manipulation of orthographic variables alter spoken responses. Commonly used variables include the degree of orthographic similarity between stimulus pairs (commonly measured by the number of overlapping letters in alphabetic languages, or other orthographic units in non-alphabetic languages in Chinese such as radicals), orthographic consistency (whether a sound can be spelled in only one way or in multiple ways), and orthographic neighbourhood density (typically defined as the number of words that can be produced by changing a letter in a word of the same length; Coltheart et al., 1977). Effects of orthography have been well demonstrated by varying these orthographic variables. A key observation is that orthographic similarity between words, consistency, and orthographic neighbourhood density can affect lexical decisions in response to spoken words, with faster decisions for orthographically similar than for less similar word pairs (e.g., Jakimik et al., 1985), for words with consistent rhymes that can be spelt in only one way than for words with inconsistent rhymes that can be spelt in multiple ways (e.g., Ziegler & Ferrand, 1998), and for words with many orthographic neighbours compared to those with fewer neighbours (e.g., Ziegler et al., 2003).

In terms of experimental tasks employed to examine orthographic effects, early studies of orthographic effects on spoken word recognition adopted meta-phonological tasks, in which participants are required to explicitly access phonological knowledge to be able to make a response. For instance, in a seminal article, Seidenberg and Tanenhaus (1979) presented participants with a pair of words in a trial, and asked them to make a judgement on whether word pairs shared a rhyme or not. Orthographic similarity of word pairs significantly influenced rhyme judgements on spoken words: Rhyme judgements were made faster for word pairs that were orthographically similar (e.g., *tie-pie*) than for orthographically less similar word pairs (e.g., *tie–rye*). Other meta-phonological tasks such as phoneme monitoring (Frauenfelder et al., 1990), rhyme detection (Ziegler et al., 2004), and tone judgement (Pattamadilok et al., 2008) have also reported similar orthographic effects. However, the validity of orthographic effects obtained with meta-linguistic tasks has been questioned on the basis that effects might reflect sophisticated response strategies due to explicit access to orthographic representations in order to assist abstract phonological judgements. Similarly, in the lexical decision task (see above), participants might also consciously retrieve orthographic forms to facilitate judgement of the lexical status of a spoken word, rather than automatically activate orthographic information (e.g., Cutler et al., 2010; Damian & Bowers, 2009).

Subsequent studies have demonstrated orthographic effects in more natural tasks which do not require the explicit retrieval of phonological/orthographic representations or lexical status (Pattamadilok et al., 2009, 2014; Peereman et al., 2009; Qu & Damian, 2017; Qu et al., 2018). Interestingly, orthographic effects appear to be more variable in shadowing (e.g., Pattamadilok et al., 2007; Rastle et al., 2011; Ventura et al., 2004; Ziegler et al., 2004). Two possible explanations for reported null effects in shadowing are that orthographic effects only emerge in tasks which, unlike shadowing, involve a decision component, or that they require lexical involvement to emerge whereas shadowing can be carried out sublexically (Ventura et al., 2004). A further possibility suggested by Rastle et al. (2011) arises from the relative time course of phonological versus orthographic activation: shadowing can be carried out based on phonological activation alone, but the extra time required to carry out for instance auditory lexical decisions allows orthographic effects to emerge. However, findings from electroencephalography (EEG) studies argue against this possibility. For instance, Pattamadilok et al. (2009) combined EEG measurements with a behavioural task in which participants pressed a response button when a given word belonged to a semantic category, and withheld their response otherwise. On no-go trials, orthographic consistency and word frequency of spoken words were manipulated. EEG results revealed a clear orthographic consistency effect and a word frequency effect. Critically, the orthographic consistency effect occurred before the onset of the word frequency effect (an indicator of lexical access), suggesting that orthographic representations are activated before lexical access occurs, rather than taking place at a later decisional or post-lexical stage. Overall, evidence that orthographic information influences spoken-word recognition emerges in some but not all experimental manipulations and paradigms (see, e.g., Hallé et al., 2000; Ziegler & Ferrand, 1998; Ziegler et al., 2004, for additional evidence). It also remains to be seen whether effects of this type extend to conversational speech (Mitterer & Reinisch, 2015).

The studies reviewed above were conducted with alphabetic languages which have a systematic mapping between spelling and sound. For these languages, it is perhaps not surprising that orthography could affect spoken word recognition. In non-alphabetic languages such as Chinese**,** spelling and sound are largely dissociated from one another, and hence co-activation of orthographic codes in spoken word processing is perhaps less obvious. Nonetheless, evidence from experiments conducted in Chinese suggests that orthographic properties do indeed constrain the processing of spoken words. For instance, Zou et al. (2012) manipulated orthographic and phonological overlap between prime-target pairs in an auditory lexical decision task. Based on their finding that orthographic similarity modulated ERP amplitudes, Zou et al. argued that orthographic information is activated during Chinese spoken word recognition. In another study, Chen et al. (2016) investigated effects of orthographic consistency on Chinese spoken word recognition via a task in which participants judged whether or not a spoken word represented an animal. Event-related potential (ERP) results showed that orthographic consistency, which was assumed to index orthographic variation at the radical level, modulated the amplitude of N400. In a semantic relatedness judgement task, Qu and Damian (2017) asked Chinese speakers to judge whether spoken word pairs were related in meaning or not, and orthographic similarity between words was found to affect response latencies. These findings suggest a role of orthography in the processing of Chinese spoken words which is similar to the one shown in alphabetic languages (see above).

The studies outlined above were conducted in individuals' native language (L1). It is of theoretical interest to examine the role of orthography in non-native (L2) spoken word processing, given that the acquisition of orthographic representations differs substantially in L1 and L2. In L1, orthographic representations are only learned after phonological representations have long been established, whereas in L2 the sound and spelling of words are often learned in conjunction, hence cross-modality effects may be stronger in L2 than in L1. On the other hand, lexical codes are typically less integrated and stable in L2 than in L1 and this might lead to weaker orthographic effects. Qu et al. (2018) tested Tibetan-Chinese bilinguals in their L2 using the semantic judgement task on spoken word pairs (see above) and reported orthographic effects which were almost twice as large as those obtained from L1 listeners in the same task (Qu & Damian, 2017). Bassetti et al. (2021) tested Italian-English bilinguals who listened to pairs of English homophonic words, with a target sound which was spelled with a single letter or two letters. The variation in the number of letters used in the spelling (one or two) led L2 English listeners to perceive an illusory contrast between short and long sounds in spoken English, a contrast that does not actually exist in the language. The findings suggest that spelling influences speech perception in L2. Overall, a limited number of existing findings suggest a role of orthography in second-language speech perception.

## Orthographic effects on spoken word production

As summarised above, the possibility of cross-modality effects on spoken word recognition has been discussed for several decades. Whether similar cross-modality effects emerge in spoken production rather than recognition is a separate issue. Word recognition is 'bottom-up', and so perhaps it makes sense that the listener makes use of all available information, including orthographic codes, to identify the signal. By contrast, language production is 'top-down', and it is intuitively less clear why for instance in a paradigmatic production task such as picture naming, orthographic properties of produced words should be relevant. Nonetheless, it has been claimed that empirical evidence suggests "a highly interactive language system in which there is a rapid and automatic flow of activation in both directions between orthographic and phonological representations", in perception and in production alike (Rastle et al., 2011, p. 1,588). Relative to the abundance of findings on orthographic effects on spoken input processing, there are fewer studies on spoken production and the evidence is less consistent, with several positive findings (e.g., Bürki et al., 2012; Damian & Bowers, 2003; Gaskell et al., 2003; Han & Choi, 2016; Rastle et al., 2011) contrasting with null findings (see e.g., Alario et al., 2007; Bi et al., 2009; Biedermann & Nickels, 2008; Chen et al., 2002; Damian & Bowers, 2009; Franck et al., 2003; Roelofs, 2006; Saletta et al., 2016; Zhang & Damian, 2012).

In an early study with the aim of exploring the role of orthography in spoken production, Lupker (1982) adopted the picture-word interference task in which speakers name pictures while ignoring visual distractor words. Compared to a control condition where pictures and words were unrelated in form, distractors that rhymed with the picture name but differed in spelling of the vowel (picture: plane; distractor: brain) generated significantly less priming than distractors that shared both spelling and sound of the rime (e.g., picture: plane; distractor: cane; Experiment 2). These findings suggest that the orthographic similarity between picture labels and written distractor words influenced the speed of picture naming. However, Damian and Bowers (2009) failed to replicate the effect of orthographic similarity in the picture-word task when using auditory (rather than visual) distractor words. This finding indicates that orthographic effects in this task might only emerge in the presence of orthographic information, hence the inference that spoken production always involves orthographic activation is questionable.

A similar inference has been drawn from a different paradigm (known as 'implicit priming', 'form preparation', or 'cyclic blocked naming') in which speakers repeatedly produce small sets of spoken words in response to cue words or objects, and relatedness among response words within a set/block is manipulated. Word-initial phonological overlap facilitates spoken response latencies (e.g., Meyer, 1990; Meyer & Schriefers, 1991) and this finding has been interpreted as advance planning of the overlapping word-initial portion of the responses (Roelofs, 1997). Damian and Bowers (2003) used this task but manipulated word-initial form overlap such that word-initial segments shared both spelling and sound ('coffee', 'camel', 'climate'), or shared only sound but included one response word with a different grapheme ('coffee', 'camel', 'kennel'). Facilitation obtaining from shared spelling and sound disappeared when a conflicting grapheme was among response words, supporting the contribution of orthography in spoken word production. However, this pattern has not been replicated in a range of response languages (Dutch: Roelofs, 2006; French: Alario et al., 2007; Mandarin: Bi et al., 2009; Zhang & Damian, 2012). For instance, with Chinese speakers, Bi et al. (2009) reported orthographic effects only in reading, but not in cued word generation or in object naming, indicating that orthographic effects may depend on the extent to which the task emphasizes the use of orthographic information (Roelofs, 2006). Orthographic effects arising from the implicit priming task should therefore be taken with caution, especially when visual words are used to cue response words, or response words are visually presented in the familiarisation phase, because visual presentation of stimuli may bias participants towards orthographic processing. Moreover, because in this task speakers produce a small set of response words repeatedly, they are more likely to be aware of the manipulation of orthographic overlap.

More evidence regarding an orthographic contribution to spoken production arises from the learning of artificial novel words (Bürki et al., 2012; Han & Choi, 2016; Rastle et al., 2011). Rastle et al. (2011) trained participants to learn a set of associations between novel pictures and novel spoken words. Spelling-sound consistent or inconsistent spellings were subsequently introduced on the second day, and the influence of these spellings on speech processing was assessed by tasks not explicitly involving orthography on the third day. Results showed that there was an effect of orthography on novel picture naming, with spelling-consistent words produced faster than inconsistent words, and this effect emerged immediately following the introduction of the spellings of words and it persisted in testing on the third day. Based on this evidence the authors argued for an interactive language architecture in which there is a rapid and automatic flow of activation in both directions between orthographic and phonological representations, and thus orthographic information will be coactivated when phonological representations are retrieved.

Positive evidence comes from a task in which speakers name coloured objects as adjective-noun phrases ('red boat') and phonological overlap between adjective and noun has been shown to generate facilitation (e.g., Damian & Dumay, 2009). Qu & Damian (2019a) investigated the role of orthography in spoken word production using this task, and showed that for native Chinese speakers, overlap between the orthographic (rather than the phonological) representations of colour and object name (e.g., '棕枕头', 'brown pillow') also facilitated responses, despite the fact that the task did not involve the presentation of any orthographic information, and object names were verbally presented to participants (Experiment 2).

Research on the role of orthography in L2 spoken production is rather limited. In one study, Qu & Damian (2019b) used a coloured object-naming task with adjective-noun phrases and found facilitation effects in Tibetan-Chinese bilinguals when responding in their L2 (Chinese), suggesting a role for orthographic influences. In a more recent study (Nimz & Khattab, 2020), Polish-German bilinguals were presented with long vowels (/eː/,/aː/,/oː/) and their short counterparts (/ɛ/,/a/,/ɔ/), with vowel length either marked or unmarked in the orthographic representation (long vowels were marked with a lengthening 'h', while short vowels were followed by double consonants). Duration measurements in picture naming responses revealed that orthographic marking facilitated more native-like production of the short-long vowel contrast for these bilinguals.

As can be appreciated from the overview above, the issue of whether orthography plays a role in the perception and production of spoken words has not been fully resolved. Further, what factors might modulate orthographic effects in each modality of spoken processing is poorly understood.

## Phonological effects on written word recognition

Reading constitutes one of the core areas of psycholinguistic research. It has been a long-standing research question whether recognizing written words involves, and perhaps even requires, the activation of phonological codes. A role of phonology in written word recognition would be predicted by many existing models of visual word recognition. For instance, van Orden's (1987; van Orden et al., 1988, 1990) verification model stipulates that access to semantic knowledge from print is entirely mediated by phonological codes. By contrast, the dual-route model of reading (Coltheart et al., 2001) stipulates that semantic information can be accessed from print via two separate routes: by a direct access route, semantic information is accessed via orthographic representations, whereas via an indirect access route, readers use the knowledge of the correspondence between letters and sounds to transfer spelling into phonological codes, and use these sound-based codes to activate semantic information of words.

In the context of the current article, we are primarily concerned with establishing and quantifying the existence of phonological effects on reading. Doing so is made more difficult by the fact that a good portion of the experimental literature on reading involves tasks which require explicit phonological access, and indeed, many of the leading theoretical and computational frameworks of reading (e.g., Harm & Seidenberg, 1999; Perry et al., 2007) are primarily models of reading aloud, i.e., they attempt to account for how orthographic codes are transformed into phonological codes. In the real world reading does not typically involve pronunciation, and so regarding the question of whether reading involves co-activation of phonological codes, the primary question is whether this is the case in silent reading.

Existing literature (see below) seems to present a broad consensus that phonology is activated in the reading of individual words and in sentence-level reading. Support for the involvement of phonology in tasks which require reading but no pronunciation comes from so-called homophone (or pseudohomophone) effects. Early studies used the lexical decision task in which participants classify letter strings into words or nonwords, and it was found that lexical decisions on pseudohomophone foils took longer than on matched non-homophonic nonword stimuli (Coltheart et al., 1977; Rubenstein et al., 1971). An explanation for this effect is that processing a pseudohomophone foil activates the phonological representation of its corresponding homophonic real word which in turn activates its lexical entry, making it more difficult to correctly reject the pseudohomophone. However, it has been questioned whether the pseudohomophone effect bears on how real words are processed, because the effect is demonstrated on nonwords whose processing could involve more robust phonological coding than that of words (Coltheart et al., 1977; van Orden, 1987; however, it should be noted that there also is a homophone effect on real words, with homophone words taking longer to classify than matched non-homophonic words; Barry, 1981).

Homophone effects have also been reported in semantic tasks. In a seminal study, van Orden (1987) adopted a semantic categorization task in which participants judge whether a word is an exemplar of a specified category. For example, for the flower category, the targets were either true exemplars (e.g., ROSE), homophones of true exemplars (e.g., ROWS) or spelling similar controls (e.g., ROBS). Participants made more errors when they responded to homophones than spelling controls. This interference effect was regarded as reflecting automatic activation of phonological representations of the homophone ROWS and phonological representations strongly retrieve the lexical entry of the category exemplar ROSE, which in turn enhances participants' propensity to misidentify ROWS as the flower ROSE. These findings were taken as evidence for the dominant role of phonology in processing visual words.

The homophone effect has been combined with various tasks and has been replicated in different languages (Besner & Davelaar, 1983; Davidson, 1986; Folk & Morris, 1995;

Taft, 1982; Underwood & Thwaites, 1982). For instance, in a variant of the Stroop task which has been used to explore the automaticity of phonological activation of written words, participants name the colour of nonwords which are pseudohomophones of colour words (e.g., 'bloo', which sounds like 'blue'). Relative to a baseline condition, the colour of incongruent pseudohomophones (e.g., 'bloo' presented in red ink) took longer to name (e.g., Spinks et al., 2000), an effect which suggests the automaticity of phonological activation from the printed distractor nonwords. However, the informativeness of Stroop-like phonological effects has been challenged (Parris et al., 2022): because the word/nonword and its colour constitute an integrated entity, it is possible that effects observed in the task do not reflect the automaticity of underlying processes but rather arise because the word inadvertently receives some attention. Notwithstanding, Stroop-like effects indicate that phonological information is automatically activated, at least in the case of spatially and temporally overlapping stimuli. Further evidence comes from 'backward masking' experiments in which a target word is briefly shown and then obscured by a non-word mask. Results from backward masking indicate that masks that are phonemically similar to the target enhance identification of the target word to a greater extent than masks that are graphemically similar, or masks that are both phonemically and graphemically unrelated (Perfetti & Bell, 1991; Perfetti et al., 1988).

In addition to individual words, phonological properties of words can also affect sentence comprehension. Sentence-level investigations reveal detrimental effects of phonological overlap among sentence constituents. Specifically, reading speed is slowed when a sentence has phonologically similar words, relative to non-overlapping control sentences (Acheson & MacDonald, 2011; Frisson et al., 2014; Keller et al., 2003; Kennison et al., 2003; Kush et al., 2015; McCutchen & Perfetti, 1982; Paterson et al., 2009; Robinson & Katayama, 1997; Zhang & Perfetti, 1993). In addition, the tongue twister reading task combined with eye-tracking reveals longer reading time on the tongue twisters, relative to controls (e.g., Rayner et al., 2012). In combination, existing evidence supports the involvement of phonological activation in reading, at least for speakers of languages with alphabetic orthographic systems (for masked priming, see, e.g., Lukatela et al., 2001; Perea & Pérez, 2009; Rastle & Brysbaert, 2006; Ziegler et al., 2014; for semantic categorization, see Lee, 2009; Nagahara et al., 2006; Ota et al., 2009; Wang et al., 2003; and for the boundary paradigm in eye-tracking studies, see Blythe et al., 2015; Winskel, 2011; Yan et al., 2009). These and other findings support the broad inference that even when the reading task does not require covert pronunciation, phonological codes undergo co-activation.

Consideration of the variations in orthographic transparency of different languages opens the possibility that visual word recognition places different demands on readers in languages with deep and shallow orthographies. Frost et al. (1987) proposed the orthographic depth hypothesis, according to which reading in languages with deep orthography primarily relies on a direct pathway to the lexicon, while readers in languages with a shallow orthography predominantly employ the indirect phonological route. Therefore, experimental findings obtained with English readers cannot be automatically generalised to languages with a more transparent orthography. For example, Geudens and Sandra (1999) highlighted differences between English- and Dutch-speaking children in their utilisation of onset-rime units during reading. Specifically, due to the considerable irregularity within the English orthographic system, proficient English readers tend to rely on a direct visual pathway for word recognition. However, this shift in reading strategy may not occur in languages with more consistent grapheme-phoneme correspondences.

How does the role of phonology differ across languages with different forms of writing systems? This question has attracted attention and motivated a number of research studies over past decades (for a review, see Li et al., 2022; Perfetti et al., 2005). The Chinese writing system, as a logographic language, constitutes an extreme of the orthographic transparency spectrum, with only negligible correspondences between orthography and pronunciation. Given this, one might expect that phonology would play a secondary, or even negligible, role in Chinese reading, with readers primarily relying on direct access to meaning from the orthography itself. However, while it remains unclear whether phonology actively mediates access to meaning, or phonology plays a secondary, more supplementary role, a growing body of research indicates that Chinese readers do indeed activate phonological information during reading (e.g., Chua, 1999; Kong et al., 2010; Spinks et al., 2000; Tan et al., 1995; Zhou & Marslen-Wilson, 1999).

All the research discussed above has focused on native speakers. However, questions arise regarding the extent to which phonological activation occurs in L2 written word recognition among bilingual speakers. Existing studies indicate that homophone effects observed in native speakers'visual word recognition also extend to non-native speakers, suggesting that phonological information is processed in L2 written word recognition. For instance, Ota et al. (2010) found that, like native English speakers, non-native speakers of English were slower and less accurate in rejecting word pairs with homophones (e.g., MOON – SON) compared to spelling controls (e.g., MOON – SIN). In another study, Lupker et al. (2015) demonstrated that in a same-different task, Japanese-English bilinguals responded more quickly to English target words when preceded by phonologically similar Japanese nonwords, compared to when preceded by unrelated nonwords. More recently, Commissaire et al.

(2019) explored phonological activation in visual word recognition in young French-English bilinguals. They found that these bilinguals took longer to respond to pseudohomophones (e.g., words that sound like real L2 words) compared to control non-words in a lexical decision task. These findings suggest automatic phonological activation during L2 written word processing.

## Phonological effects on written word production

Most of the work on the role of phonology has investigated input processing (i.e., written word recognition) but comparatively little research has been directed at orthographic output processes (i.e., written production). Notwithstanding, it is a long-standing issue whether phonological codes affect written production. According to the 'phonological mediation' view proposed by early theorists (e.g., Luria, 1970), prior retrieval of sound-based codes is necessary for access to orthographic output representations. This account is compatible with phonologically based errors in spelling and typing such as homophone substitutions (e.g., 'there' spelled as 'their') and phonologically plausible nonwords (e.g., 'dearth' spelled as 'dirth'). However, some neuropsychological studies argued against the phonological-mediation view, by the observation of a dissociation between spoken and written production in case studies. For instance, patients with acquired brain damage were unable to name objects orally due to deficits at the level of the phonological lexicon, but they were able to retrieve orthographic representations and write down their names (e.g., Bub & Kertesz, 1982). Based on these findings from neuropsychological studies, according to the orthographic-autonomy view (Rapp et al., 1997) orthographic representations can be retrieved directly from semantics without the mediation of phonological codes.

It should be noted that evidence from patients does not necessarily imply that intact writing is unaffected by phonological codes. Because the availability of inexpensive digital graphic tables allows the measurement of characteristics of written language, a rising number of experimental studies have been conducted with unimpaired individuals to explore the involvement of phonological coding in written production (e.g., Bonin et al., 1998; Bonin et al., 2001; Breining & Rapp, 2019; Qu & Damian, 2020; Roux & Bonin, 2012; Shen et al., 2013). As will be shown below, the existing literature reports mixed evidence, with a number of supportive findings contrasting with a range of null findings. In a masking procedure in which objects are preceded by briefly presented and masked non-words, Bonin et al. (1998) manipulated the orthographic and phonological similarity between non-words and object names. Orthographic similarity between prime non-words and target objects generated a priming effect in written response latencies of object names, but varying the degree of phonological similarity while holding orthographic similarity constant failed to affect written latencies, suggesting a limited role of phonology in writing. These results contrast with findings from studies using the same masking procedure with Chinese speakers (Qu et al., 2016) which demonstrated a phonological overlap effect, i.e., phonologically related but orthographically unrelated prime words facilitated written production of target object names.

In addition, researchers have used the picture-word interference (PWI) task (see section on O*rthographic effects on spoken word production*) but with written rather than spoken object naming. In a PWI task conducted with English speakers, Zhang and Damian (2010) varied the degree of phonological overlap between distractor words and object names, and manipulated the onset of the distractor words relative to the onset of objects (stimulus-onset asynchrony, SOA) which allows us to examine the time course of cognitive processes underlying object naming. Results showed phonological effects at an earlier SOA, suggesting early phonological encoding when accessing orthographic representations. Similar phonological effects at early SOAs were reported by Qu et al. (2011) with Chinese speakers. Roux and Bonin (2012) found facilitatory effects from distractors whose names shared an initial letter but not the initial sound (e.g., CANARD and CITRON) but *no* facilitation from distractors whose names shared an initial sound but not the initial letter (e.g., CAKE and KITE). Their results supported the orthographic autonomy hypothesis according to which orthographic retrieval involves the automatic activation of the orthographic form without phonological mediation (Bonin et al., 2012).

Overall, results from some but not all studies suggest that phonology constrains orthographic input and output processes, and it is currently unclear what factors determine this pattern.

## Potential moderators

In this section, we will introduce moderators that we included in our meta-analyses. As we could only include those moderators that are frequently reported in the literature, this list is not meant to be exhaustive.

**Experimental task** The size of a cross-activation effect may depend on task characteristics. For example, an account of orthographic effects on some speech perception tasks has been proposed (see Cutler et al., 2010, for details) according to which metalinguistic activities and lexical decision tasks encourage strategic (probably, voluntary) access to orthographic representations and hence these tasks will exhibit orthographic effects; by contrast, other tasks such as those involving semantic judgements will less obviously benefit from strategic orthographic access and hence responses will be unaffected by orthographic manipulations. Similarly, in spoken production, it has been argued that orthographic effects may depend on the extent to which the task emphasizes the retrieval of orthographic representations (Alario et al., 2007; Bi et al., 2009; Roelofs, 2006). This suggests that cross-activation effects could be affected by task characteristics.

**Alphabeticity and orthographic transparency** Writing systems, as scripts comprising of a collection of written symbols, differ in the extent to which they represent spelling-to-sound correspondences. A broad distinction is between alphabetic and non-alphabetic orthographic systems, with the former (e.g., English, Spanish and French) using letters or letter combinations to encode spoken phonemes whereas the latter (e.g., Chinese or Japanese Kanji) using orthographic symbols which do not correspond to spoken sounds. Alphabetic systems also vary in their degree of orthographic transparency: in shallow orthographies such as Serbian, spelling-to-sound correspondences are almost perfectly regular, whereas in deep orthographies such as English, the relation of spelling to sound is often more opaque, and many languages with alphabetic systems (e.g., Spanish, Italian, Finnish) have an intermediate degree of consistency.

It is possible that the orthographic depth of a given language influences the degree to which orthography and phonology interact. Findings across different languages provide preliminary evidence for this claim (e.g., Frost et al., 1987; Roelofs, 2006). For instance, an orthographic effect was reported in spoken production of English words by Damian and Bowers (2003), whereas no such orthographic effect was found in Dutch word production (Roelofs, 2006). As hypothesized by Roelofs, the interplay of orthography and phonology in speech production is perhaps related to the degree of orthographic depth (but see Alario et al., 2007, for evidence against the claim). Relatively little work exists which compares alphabetic to non-alphabetic languages. For instance, the fact that in the Chinese writing system few mappings exist between orthographic symbols and pronunciation renders it possible that Chinese readers access the meaning of a word without the use of phonology. Contrary to this prediction, evidence suggests the involvement of phonology even in Chinese reading, hence Perfetti and colleagues (e.g., Perfetti et al., 1992) proposed a "universal phonological principle" according to which reading involves phonological encoding independent of the orthographic system. However, this principle does not necessarily imply that the magnitude of phonological effects is consistent across writing systems, and it is unclear whether the orthographic depth of a given language is a relevant factor.

In the meta-analyses reported below, we investigated orthographic depth as a potential variable of interest in a twofold manner. First, we classified all included studies according to whether the target language used an alphabetic or non-alphabetic script ('alphabeticity'). This moderator reflects a fundamental division in how a given writing system represents a spoken language. Second, we aimed to further explore the potential role of 'orthographic depth', and particularly variations among alphabetic languages. Despite the fact that some alphabetic languages are more transparent than others, quantifying the degree of regularity between orthographic symbols and pronunciations is challenging (for a recent overview, see Borleffs et al., 2017). Largely but not entirely based on a classification suggested by Seymour et al. (2003), we categorised each language/script into one of four categories of 'orthographic depth':

(1) Regular/shallow (Serbian, Korean, Katakana, Hiragana, Romaji);
(2) Reasonably regular (German, Greek, Spanish, Dutch, Portuguese, Basque);
(3) Substantially irregular (English, French, Thai, Hebrew, Persian), and
(4) Largely opaque (Chinese; Japanese Kanji).

**Nativeness** Spoken language is acquired at an early age; for literate individuals, literacy is acquired much later in life. It is possible that cross-modality effects are restricted to individuals with strong orthographic representations. Because most relevant empirical studies have been conducted with highly literate individuals (often university students), it is difficult to determine in a meta-analysis whether the strength/quality of orthographic representations is a factor which might affect cross-modality effects. A related aspect is whether there are differences between individuals operating in their native (L1) and non-native (L2) languages. Because many bilinguals learn their L2 based on written and spoken codes simultaneously or perhaps even predominately via reading, orthographic and phonological codes might be more closely intertwined than for native languages. On the contrary, it is almost certain that for most bilinguals, non-native language representations are less stable and integrated than corresponding native representations, which could imply less automatic co-activation of spelling and sound. Qu and colleagues (2017, 2018, 2019a, 2019b) investigated the impact of orthography on spoken word recognition and production with L1 and L2 speakers of Chinese, and found an orthographic effect in both L1 and L2, but the effect was more pronounced in L2 than L1. In our meta-analyses, we coded studies according to whether participants processed or generated their native or non-native languages.

It is acknowledged that these moderators could to some extent be confounded with one another: for instance, it is possible that cross-modality effects are more pronounced in a bilingual's non-native compared to their native language system, but whether or not this is true might itself depend on the nature of their orthographic systems in their L1 and L2.

## Meta-analyses

We conducted four meta-analyses to assess the magnitude of cross-modality effects in the four target domains (spoken word recognition and production, written word recognition and production). First, we examined whether the literature provides clear evidence in favour of cross-modality effects by conducting four meta-analyses using a similar procedure, and estimating the overall effect size of the respective findings in each domain. Second, we examined the influence of potential moderators (see previous section) on these cross-modality effects, namely: experimental task, alphabeticity, orthographic depth, and participants' nativeness of target language.

Below we used the term number of *effect size* rather than *experiment* or *study* since one study may contain multiple experiments and one experiment may involve multiple manipulations, and there are also cases where the same sample of subjects participated in different tests or experiments. We defined an effect size as a part nested within a study, with manipulations that are relevant to the aims of our meta-analyses. Therefore, an effect size is not necessarily equivalent to a sample, study or experiment, with one study potentially containing multiple relevant effect sizes. To control for the dependency effects among effect sizes, we conducted multilevel meta-analyses and performed robust variance estimation for our models (Hedges et al., 2010).

## Literature search

All literature searches were conducted in the databases *PsycINFO, PsychArticles, Psychology and Behavioral Sciences Collection in EBSCO host*, and *Web of Science*. We used the following search strings for the different meta-analyses and the search was implemented to detect studies published between 1971 and June 2024. Regarding *orthographic processing in speech perception*, search strings were *(speech OR spoken word) AND (recognition OR perception) AND (orthographic processing OR orthography) NOT (dyslexia OR impaired OR patients)*. With this search strategy, we identified 2,129 items before a series of screening procedures. Regarding *orthographic activation in spoken production*, we used the search strings *(speech OR spoken word) AND (production OR speaking) AND (orthographic processing OR orthography) NOT (dyslexia OR impaired OR patients)*, and we identified 1,701 items. Regarding *phonological processing in written word recognition*, the search strings were *(word reading OR visual word processing) AND (phonological processing OR phonology OR inner speech) NOT (dyslexia OR impaired OR patients)*, and 7,609 items were identified. Regarding *phonological activation in written word production*, the search strings were: *(word writing OR written word production) AND (phonological processing OR phonology) NOT (dyslexia OR impaired OR patients)*, and 1,622 items were identified.

## Inclusion and exclusion criteria

After deleting duplicate records, we used the following common criteria to preliminarily select studies for further screening in all four meta-analyses:

(1) Publications had to be in English due to the language background of the authors.
(2) Only empirical studies were included, i.e., review articles, conference abstracts, correspondence, letters, and other unspecified non-data entries were excluded.
(3) We focused exclusively on samples with healthy participants. Records were excluded when only case studies or participants with a history of neurological or language problems were reported.
(4) Via careful screening of titles and abstracts, only studies relevant to the considered issues were included.

For the remaining records, we examined and assessed full articles for eligibility according to the following criteria:

(1) Only studies in which response latencies were measured and reported as the dependent variable were included.
(2) Studies were included only when the studies reported sufficient statistical information to compute an effect size.
(3) Samples were excluded when participants were illiterate.

Finally, we adopted the following criteria to carefully screen the remaining publications:

(1)(2) Publications were excluded when studies were not relevant to the role of orthography in listening or speaking, or the role of phonology in reading and writing. Because our interest lies in cross-activation of linguistic representations, samples were excluded when only meaningless sounds were presented in listening and speaking tasks, and when only numbers or symbols were presented in reading tasks.

Following these screening procedures, we examined the reference sections of all qualifying articles for citations and identified additional studies for inclusion, and we checked the reference sections of relevant literature reviews (forward and backward search of citation). Application of these criteria resulted in the selection of 33 studies with 93 effect sizes in spoken word recognition, 17 relevant studies with 34 effect sizes in spoken word production, 76 studies with 178 effect sizes in written word recognition, and 15 studies with 28 effect sizes in written word production. See Fig. 1 for flow diagrams of the literature screening procedures of our systematic search.

## Data coding

We coded all samples on the four variables: Experimental task (classified; see below), Alphabeticity of the writing system of the target language (dichotomous; alphabetic vs. non alphabetic language), Orthographic depth of the target language (regular, reasonably regular, substantially irregular, largely opaque), and Nativeness of target language for participants (dichotomous; native vs. non-native). As experimental tasks vary substantially across modalities, a modality-specific variable was coded for task, as follows. For *spoken word recognition:* meta-linguistic task, primed lexical decision task, lexical decision, shadowing, semantic judgement, and novel word learning; for *spoken word production:* picture naming, primed picture naming, implicit priming/blocked naming, picture-word interference, Stroop task, and word generation; for *written word*

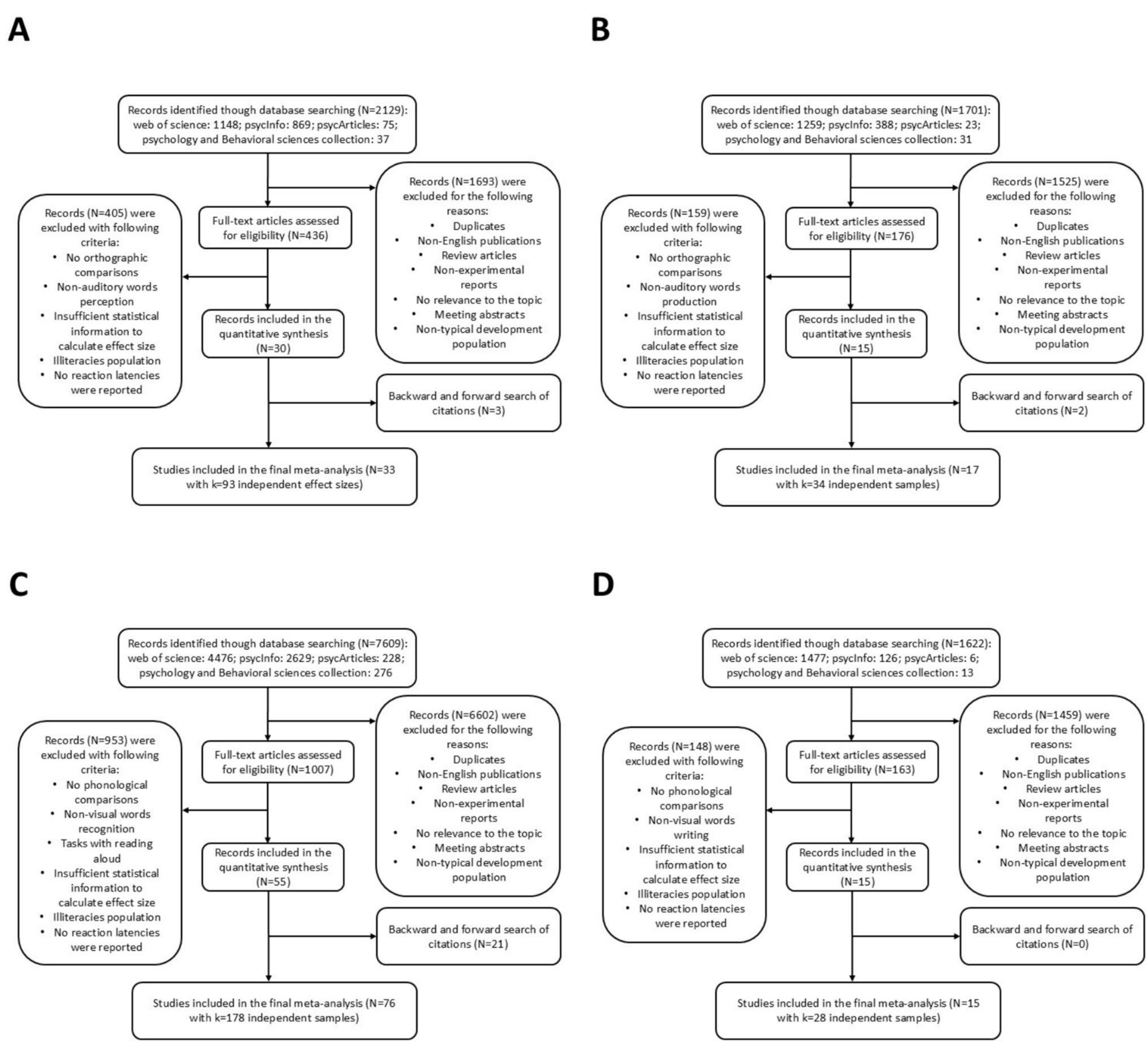


**Fig. 1** Flow diagrams of the systematic review process investigating: (**A**) orthographic effects on listening, (**B**) orthographic effects on speaking, (**C**) phonological effects on reading, (**D**) phonological effects on writing

*recognition:* lexical decision, primed lexical decision, covert reading, semantic judgement, visual word recognition, Flanker task, and same-different task; for *written word production:* implicit priming, copying task, picture naming, picture-word interference task, and Stroop task. To guard against coder drift (i.e., changes in coder output caused by fatigue and/or practice effects), each study was also reviewed by a doctoral-qualified researcher (the last author of this article) and discrepancies were resolved by an expert in the field of experimental psycholinguistics.

## Computation of effect sizes

Most psycholinguistic studies use repeated-measures design in which each participant receives multiple treatment conditions. In our meta-analyses, we estimated the effect sizes from repeated-measures *t*-test or *F*-test statistics using the following conversion formula (Morris & DeShon, 2002; Rosenthal, 1991; van den Bussche et al., 2009; Wen & van Heuven, 2017):

$$d = \frac{t}{\sqrt{n}}$$

*or*

$$d = \sqrt{\frac{F}{n}}$$

in which $n$ is the number of participants. For repeated-measures designs, the following variance formula has been proposed (Morris & DeShon, 2002):

$$variance = \left(\frac{1}{n}\right)\left(\frac{n-1}{n-3}\right)\left(1 + nd^2\right) - \frac{d^2}{\left[c(df)\right]^2}$$

in which $n$ is the number of participants and the bias function *c(df)* is approximated by (Hedges, 1982):

$$c(df) = 1 - \frac{3}{4(n-2)}$$

Moreover, a few studies simply reported that an effect was not statistically significant, without reporting statistical information. Considering that meta-analytic findings may be biased if we excluded these results from meta-analyses, we followed Lipsey and Wilson's (2001) approach and replaced these non-significant results with zero for the missing effect sizes. As the goal of our study was to establish the existence, rather than the direction, of cross-modality effects, following calculation of the effect sizes we used the absolute value of negative effect sizes to replace the original data (cf., Brydges, 2019).

## Multilevel modeling for meta-analysis

Following estimation of the effect size and its corresponding sampling error for each sample, we conducted the meta-analyses in *R* version 4.2.2 software (R Core Team, 2022) with the following protocol using *'metafor'* package (Viechtbauer, 2010) and *'robumeta'* package (Fisher et al., 2017) to conduct robust variance estimation with clustering factors. To account for the issue of dependency, a multilevel approach was used throughout the whole meta-analytic procedure which addresses the nested structure of the data (e.g., Terry et al., 2020; Torka et al., 2021). To examine the overall cross-modality effect in each modality, we used a multilevel random effect model of meta-analysis with robust variance estimation, which provided a more robust estimation of $p$ values considering potential dependencies among effect sizes. Heterogeneity of effect sizes was assessed using the $Q$ test.

To explore potential moderators that may account for the heterogeneity of cross-modality effect, we conducted an analysis with a multilevel random effect model with task, alphabeticity of test language, orthographic depth, and nativeness of participants as moderators. Subgroup analyses were conducted to investigate detailed patterns of moderators by including one moderator at a time. We included a nested random effect structure in the model to capture variability associated with each moderator nested within different studies. Differences between the levels of these moderator variables (e.g., alphabetic vs. non-alphabetic, native vs. non-native) were examined using t tests.

Potential publication bias was explored by visual inspection of funnel plots and the *p*-curve method (Simonsohn et al., 2014, 2015). One-side contour-enhanced funnel plots of the data were created in which the effect size is plotted against sample variance with added contours (indicated by regions of red and orange) representing important levels of statistical significance at $.1 > p > .05$ (shaded red), and $.05 > p > .01$ (shaded orange; Peters et al., 2008). If the proportion of studies falling within these contours is overly large, i.e., a substantial number of studies are shaded orange or red, this suggests that research in the field may be affected by publication bias and/or *p*-hacking (Brydges, 2019; Ioannidis, 2008; Simmons et al., 2011). Moreover, we applied '*p*-curve analysis' to evaluate publication bias (Simonsohn et al., 2014). The *p*-curve method is based on the idea that the shape of a histogram of statistical error values depends not only on the sample sizes of studies, but also on the true effect size behind the reported data (Harrer et al., 2021). The right skewness in the distribution of *p*-values (the *p*-curve) was examined as a function of the true underlying effect; a right skewed *p*-curve would indicate that publication bias is not a concern, and a left skewed *p*-curve would suggest the presence of publication bias or so-called *p*-hacking (Ritchie

& Tucker-Drob, 2018). All the meta-analytic data and code methods of all the eligible studies and R analysis code are available via the Open Science Framework at https://osf.io/bkdj5/.

## Results

### Orthographic effects on spoken word recognition

**Main effect** Thirty-three studies with 93 effect sizes were included to assess the role of orthography in spoken word recognition. As shown in Table 1, the *Q* test was significant ($p < .001$), which indicates substantial heterogeneity. The multilevel modeling with robust variance estimation indicated a highly significant moderate overall effect size ($d = 0.61$; see Figs. 2 and 3 for a forest plot of effect sizes). The contour-enhanced funnel plot (Fig. 2A) did not show an overrepresentation of just-significant (*p* values between.05 and.01, represented by the orange area of the figure) or marginally significant (*p* values between.10 and.05, represented by the red area of the figure) results, suggesting that publication bias is less likely to be present. Moreover, the right-skewness of the *p*-curve was significant (full *p*-curve: $z = -17.99$, $p < .001$; half *p*-curve: $z = -16.75$, $p < .001$), confirming that the studies included for our analyses contain evidential value for the existence of the orthographic effect. Overall, the funnel plot and *p*-curve analysis indicate that there was no evidence for publication bias or *p*-hacking.

**Moderator analyses** Table 2 shows the results from the meta-regressions with each moderator as a predictor of effect size. To explore the pattern of moderators, estimated pooled effect sizes are shown for each subgroup of the moderators. As shown in Table 2, for the moderator *task*, orthographic effects were significant in all tasks except for novel word learning. Specifically, the effect was relatively large in lexical decision, semantic judgement, and meta-linguistic tasks and moderate in primed lexical decision and shadowing. For the moderator *alphabeticity*, the effect was significant both in alphabetic and non-alphabetic language scripts, with comparable effect size ($t = 0.08$, $p = .933$). For the moderator *orthographic depth*, effects were significant for all levels of languages, with effect size growing with increasing depth but the differences failed to reach conventional significance (*p*s $> .094$). For the moderator *nativeness*, the effects were significant for both native and non-native speakers, with no significant difference between the two groups ($t = -0.07$, $p = .945$).

### Orthographic effects on spoken word production

**Main effect** Seventeen studies with 34 effect sizes were included to assess the role of orthography in speech production. Table 1 shows substantial heterogeneity ($p_Q < .001$) and a moderate effect size with robust variance estimation ($d = 0.44$, $p < .001$; see Fig. 4 for a forest plot). The funnel plot shown in Fig. 2B does not suggest an overrepresentation of just-significant or marginally significant results. The results of the *p*-curve analysis further verify that publication bias or *p*-hacking in spoken word production is not a concern: the binomial test was significant ($p = .004$), as was the continuous test (full *p*-curve: $z = -4.85$, $p < .001$; half *p*-curve: $z = -3.74$, $p < .001$).

**Moderator analyses** As shown in Table 2, for the moderator *task*, orthographic effects were significant for picture naming and implicit priming/blocked naming tasks. The effect was moderate in picture naming and smaller in implicit priming/blocked naming. For the moderator *alphabeticity*, significant effects were found for both alphabetic and non-alphabetic languages, with the effect numerically larger in the former than the latter but with no significant difference ($t = -0.93$, $p = .357$). For the moderator *orthographic depth*, effects were significant for all levels except for the 'relatively regular' condition, with the larger effect size in 'substantially irregular' languages than that in 'largely opaque' languages but this difference was not significant ($t = 1.19$, $p = .244$). For *nativeness*, the effect was relatively small for native speakers but larger for non-native speakers, with the difference being significant ($t = 2.23$, $p = .033$).

**Table 1** Effect sizes with robust variance estimation and test of heterogeneity, separately for orthographic/phonological effects on spoken/written recognition/production

| Effect | Effect size | | | Test of heterogeneity | | |
|---|---|---|---|---|---|---|
| | *d* [95% CI] | *Z* value | *p* | *Q* | *df* | *p* |
| Orthographic effects on spoken word recognition | 0.61 [0.49, 0.74] | 9.93 | <.001 | 354 | 92 | <.001 |
| Orthographic effects on spoken word production | 0.44 [0.29, 0.59] | 5.87 | <.001 | 67 | 33 | <.001 |
| Phonological effects on written word recognition | 0.49 [0.42, 0.57] | 12.48 | <.001 | 1050 | 177 | <.001 |
| Phonological effects on written word production | 0.35 [0.22, 0.47] | 5.47 | <.001 | 80 | 27 | <.001 |

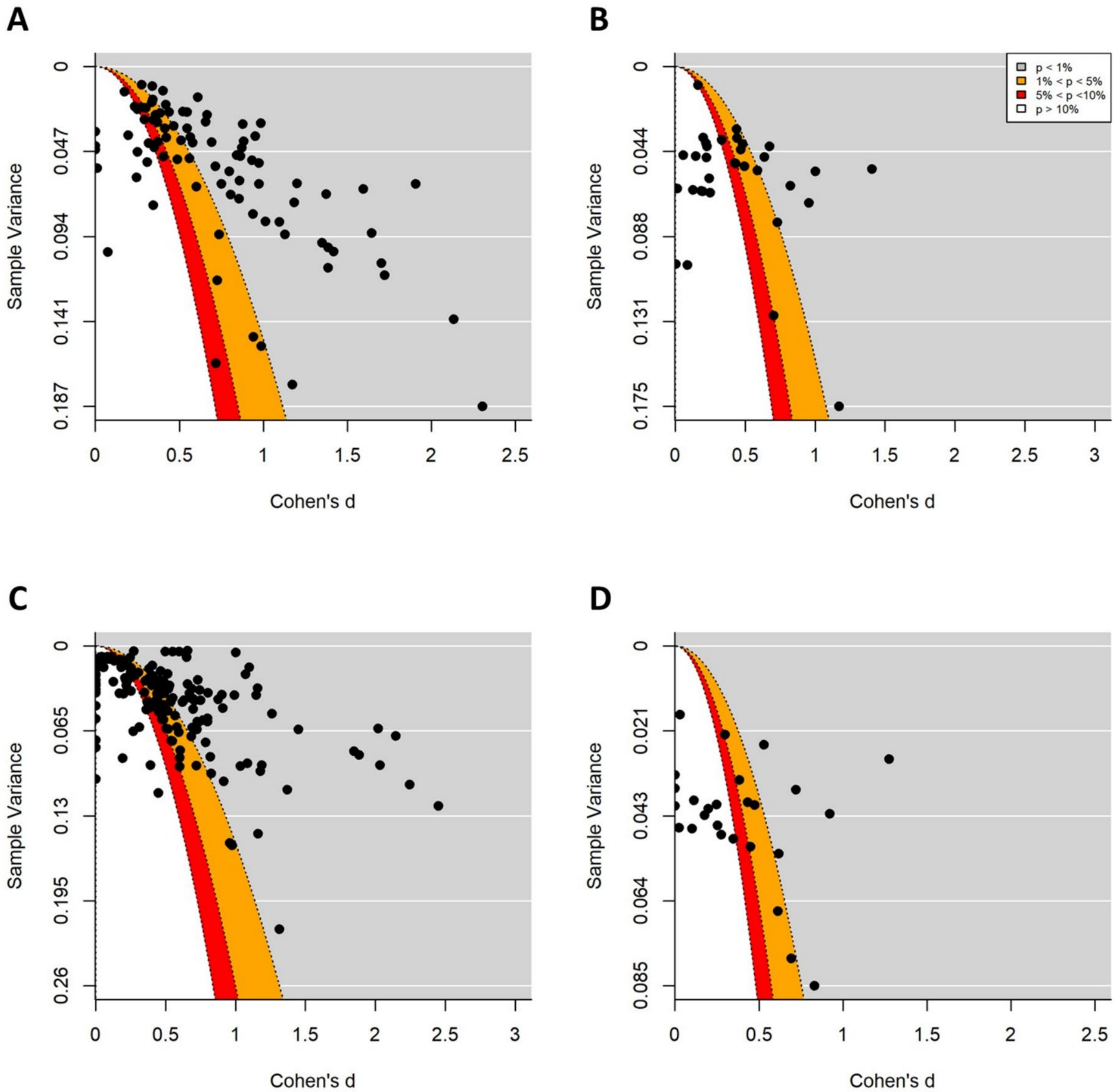


**Fig. 2** One-sided contour-enhanced funnel plots of the four meta-analyses: (**A**) orthographic effects on spoken word recognition, (**B**) orthographic effects on spoken word production, (**C**) phonological effects on written word recognition, (**D**) phonological effects on written word production. The dots indicate the studies included in the meta-analyses, and the grey, orange and red regions denote statistical significance at 0.01, 0.05, and 0.10 levels, respectively

### Phonological effects on written word recognition

**Main effect** Seventy-six studies with 178 effect sizes were included to assess phonological effects on written word recognition. Table 1 shows a moderate effect size after conducting robust variance estimation ($d = 0.49$; see Fig. 5 for a forest plot) and heterogeneity between studies ($p_Q$ <.001). The funnel plot (Fig. 2C) indicates that a number of effects falls within the just-significant and marginally significant regions, eliciting a potential concern regarding publication bias. However, the *p*-curve analysis showed a significantly right-skewed distribution of *p* values (full *p*-curve: $z = -22.70$, $p$ <.001; half *p*-curve: $z = -22.62$, $p$ <.001), indicating that the studies included in the meta-analytic procedure present evidential value.

**Moderator analyses** As shown in Table 2, for the moderator *task*, phonological effects were of medium size and significant for all tasks except for the Flanker task in which the effect just failed conventional significance, and for the same-different judgement task. For the moderator *alphabeticity*, the effect was significant for both alphabetic and non-alphabetic language, with comparable size and no significant difference between them ($t = -0.81$, $p$ =.419). For the moderator *orthographic depth*, effects were significant for all levels and did

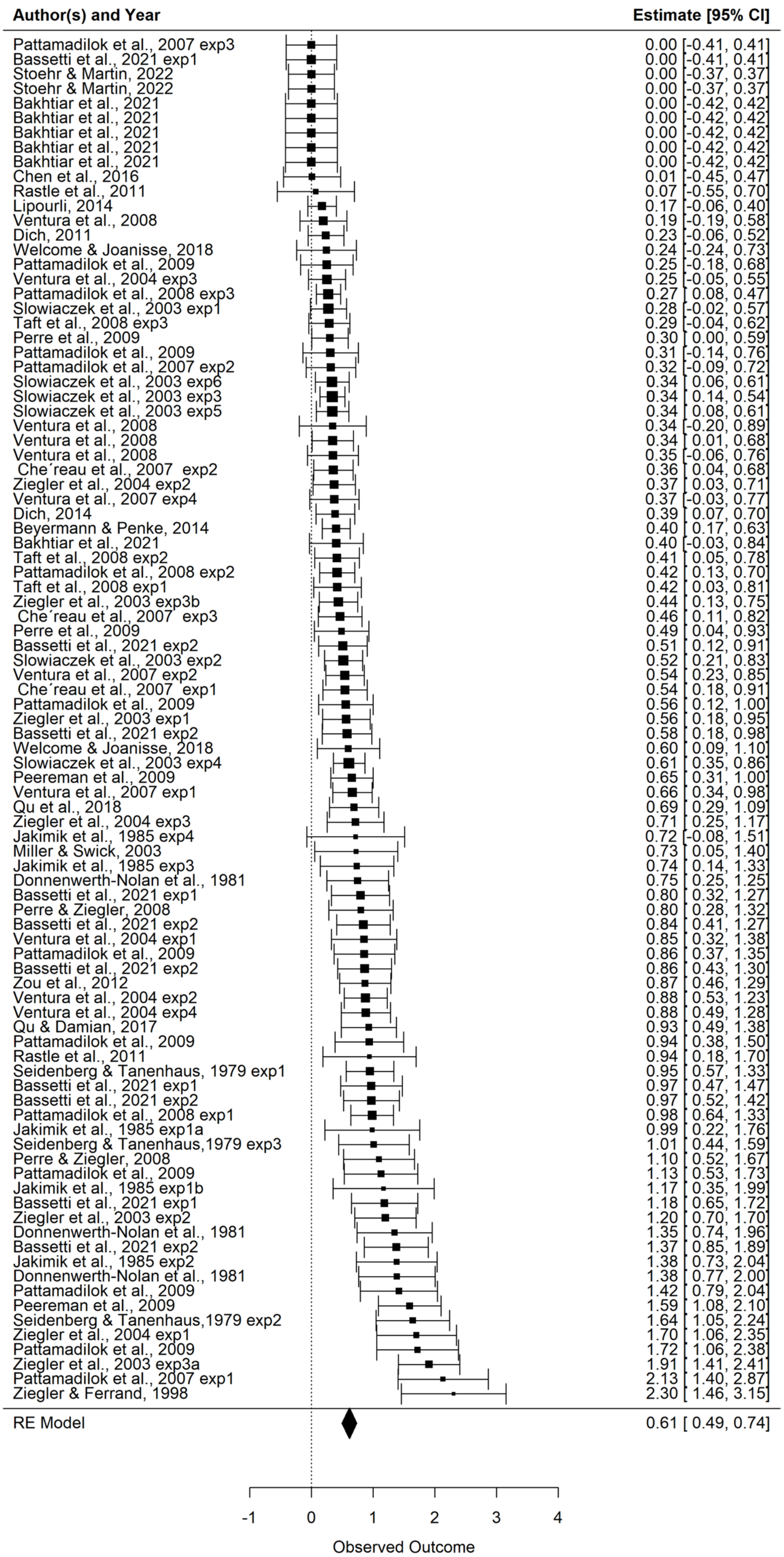


**Fig. 3** Forest plot of effect sizes for orthographic effects on spoken word recognition. The dash line denotes the null effect and rhombus indicates the overall effect size. The middle panel of the figure shows the effect size with 95% confidence interval and corresponding weight for each k

**Table 2** Cross-modality effects in each modality for each subgroup of moderators

| Subgroup | $k$ | $d$ [95% CI] | $p$ | $\tau^2$ |
|---|---|---|---|---|
| ***Orthographic effects on spoken word recognition*** | | | | |
| *Task* | | | | |
| Meta-linguistic task | 23 | 0.62 [0.34, 0.90] | <.001 | 0.12 |
| Primed lexical decision | 15 | 0.54 [0.31, 0.78] | <.001 | 0.05 |
| Lexical decision | 33 | 0.73 [0.44, 1.02] | <.001 | 0.31 |
| Shadowing | 15 | 0.50 [0.34, 0.66] | <.001 | 0.03 |
| Semantic judgement | 5 | 0.66 [0.24, 1.08] | .002 | 0.14 |
| Novel word learning | 2 | 0.42 [−0.16, 1.01] | .154 | 0.03 |
| *Alphabeticity* | | | | |
| Alphabetic language | 86 | 0.57 [0.44, 0.69] | <.001 | 0.09 |
| Non-Alphabetic language | 7 | 0.58 [0.28, 0.88] | <.001 | 0.08 |
| *Orthographic depth* | | | | |
| Shallow | - | - | - | - |
| Relatively regular | 14 | 0.39 [0.18, 0.60] | <.001 | 0.05 |
| Substantially irregular | 75 | 0.60 [0.46, 0.74] | <.001 | 0.09 |
| Largely opaque | 4 | 0.63 [0.23, 1.04] | .003 | 0.12 |
| *Nativeness* | | | | |
| Native speaker | 85 | 0.56 [0.44, 0.68] | <.001 | 0.08 |
| Non-native speaker | 8 | 0.54 [0.00, 1.08] | .049 | 0.19 |
| ***Orthographic effects on spoken word production*** | | | | |
| *Task* | | | | |
| Picture naming | 15 | 0.53 [0.25, 0.81] | <.001 | 0.14 |
| Implicit priming/blocked | 13 | 0.35 [0.15, 0.55] | .001 | 0.04 |
| Picture-word interference | 2 | 0.34 [−0.02, 0.70] | .062 | 0.01 |
| Stroop task | 2 | 0.26 [−0.08, 0.61] | .128 | 0.01 |
| Word generation | 2 | 0.35 [−0.03, 0.73] | .067 | 0.01 |
| *Alphabeticity* | | | | |
| Alphabetic language | 21 | 0.50 [0.27, 0.73] | <.001 | 0.10 |
| Non-Alphabetic language | 13 | 0.36 [0.17, 0.55] | <.001 | 0.03 |
| *Orthographic depth* | | | | |
| Shallow | - | - | - | - |
| Relatively regular | 4 | 0.27 [−0.14, 0.67] | .191 | 0.04 |
| Substantially irregular | 17 | 0.55 [0.28, 0.82] | <.001 | 0.12 |
| Largely opaque | 13 | 0.36 [0.17, 0.55] | <.001 | 0.03 |
| *Nativeness* | | | | |
| Native speaker | 31 | 0.36 [0.24, 0.48] | <.001 | 0.02 |
| Non-native speaker | 3 | 0.93[0.42, 1.44] | <.001 | 0.13 |

**Table 2** (continued)

| Subgroup | $k$ | $d$ [95% CI] | $p$ | $\tau^2$ |
|---|---|---|---|---|
| ***Phonological effects on written word recognition*** | | | | |
| *Task* | | | | |
| Lexical decision task | 65 | 0.56 [0.46, 0.67] | <.001 | 0.07 |
| Primed lexical decision | 61 | 0.40 [0.17, 0.63] | <.001 | 0.19 |
| Covert reading | 21 | 0.36 [0.21, 0.51] | <.001 | 0.05 |
| Semantic judgement | 21 | 0.51 [0.37, 0.65] | <.001 | 0.04 |
| Visual word recognition | 4 | 0.54 [0.29, 0.80] | <.001 | <.001 |
| Flanker task | 2 | 0.38 [0.00, 0.77] | .054 | 0.03 |
| Same-different task | 4 | 1.11 [−0.49, 2.72] | .174 | 1.29 |
| *Alphabeticity* | | | | |
| Alphabetic language | 155 | 0.49 [0.41, 0.58] | <.001 | 0.09 |
| Non-Alphabetic language | 23 | 0.42 [0.28, 0.57] | <.001 | 0.05 |
| *Orthographic depth* | | | | |
| Shallow | 4 | 0.31 [0.06, 0.57] | .017 | 0.02 |
| Relatively regular | 28 | 0.66 [0.10, 1.23] | .021 | 0.25 |
| Substantially irregular | 129 | 0.48 [0.39, 0.56] | <.001 | 0.09 |
| Largely opaque | 17 | 0.53 [0.37, 0.70] | <.001 | 0.04 |
| *Nativeness* | | | | |
| Native speaker | 161 | 0.45 [0.39, 0.52] | <.001 | 0.06 |
| Non-native speaker | 17 | 0.67 [0.35, 0.98] | <.001 | 0.20 |
| ***Phonological effects on written word production*** | | | | |
| *Task* | | | | |
| Implicit priming | 5 | 0.32 [−0.18, 0.82] | .202 | 0.10 |
| Copying task | 7 | 0.41 [0.27, 0.55] | <.001 | <.001 |
| Picture naming | 10 | 0.29 [0.08, 0.51] | .009 | 0.03 |
| Picture-word interference | 5 | 0.29 [0.08, 0.51] | .009 | 0.01 |
| Stroop task | 1 | 0.72 [0.28, 1.16] | .003 | 0.01 |
| *Alphabeticity* | | | | |
| Alphabetic language | 23 | 0.33 [0.20, 0.46] | <.001 | 0.03 |
| Non-alphabetic language | 5 | 0.42 [0.19, 0.65] | .001 | 0.02 |
| *Orthographic depth* | | | | |
| Shallow | - | - | - | - |
| Relatively regular | 3 | 0.54 [0.29, 0.78] | <.001 | < 0.001 |
| Substantially irregular | 20 | 0.30 [0.16, 0.43] | <.001 | 0.02 |
| Largely opaque | 5 | 0.42 [0.19, 0.65] | .001 | 0.02 |
| *Nativeness* | | | | |
| Native speaker | 26 | 0.33 [0.21, 0.45] | <.001 | 0.02 |
| Non-native speaker | 2 | 0.50 [0.16, 0.83] | .005 | 0.02 |

The table depicts the statistics examining whether the effect size for each level of the moderators is significantly different from zero. $k$ = the number of individual effects in the relevant moderator category; $d$ [95% CI] = the effect size measured by Cohen's $d$ along with its 95% confidence interval; $p$ = the significance of the moderator categories; $\tau^2$ = Random effects variance

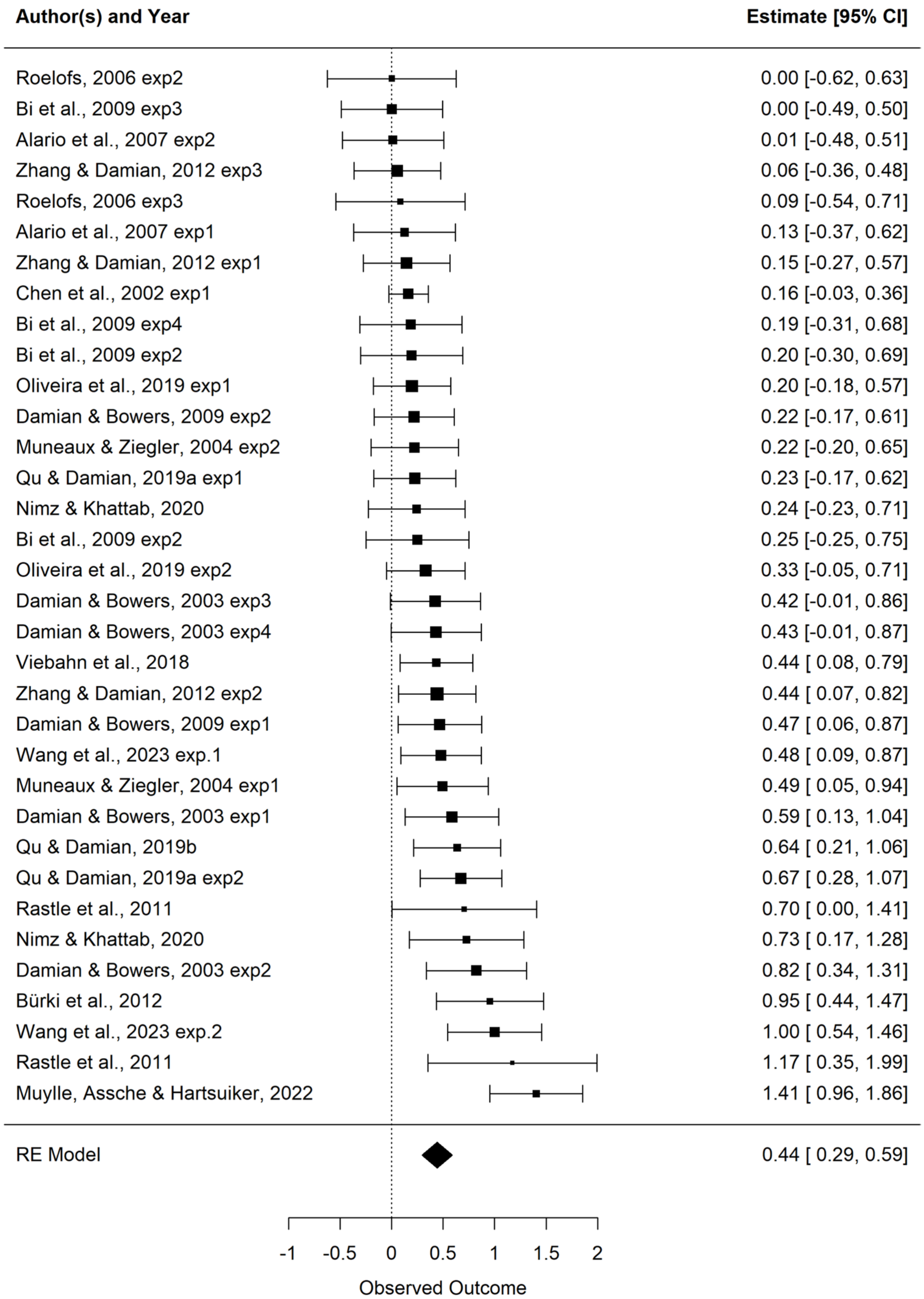


**Fig. 4** Forest plot of effect sizes for orthographic effects on spoken word production

not significantly differ among the various orthographic systems (*ps* >.147). For the moderator *nativeness*, the effect was numerically larger for non-native than for native speakers but no significant difference ($t = 1.32$, $p = .190$).

## Phonological effects on written word production

**Main effect** Fifteen studies with 28 effect sizes were included to assess phonological effects on written word production. Table 1 shows a highly significant overall small effect size with robust variance estimation ($d = 0.35$; see Fig. 6 for a forest plot) and heterogeneity between studies ($p_Q < .001$). The funnel plot shown in Fig. 2D does not suggest a publication bias. The *p*-curve analysis showed a significantly right-skewed distribution of *p* values (full *p*-curve: $z = -4.32$ $p < .001$; half *p*-curve: $z = -5.00$, $p < .001$), indicating that the studies included in the meta-analytic procedure present evidential value.

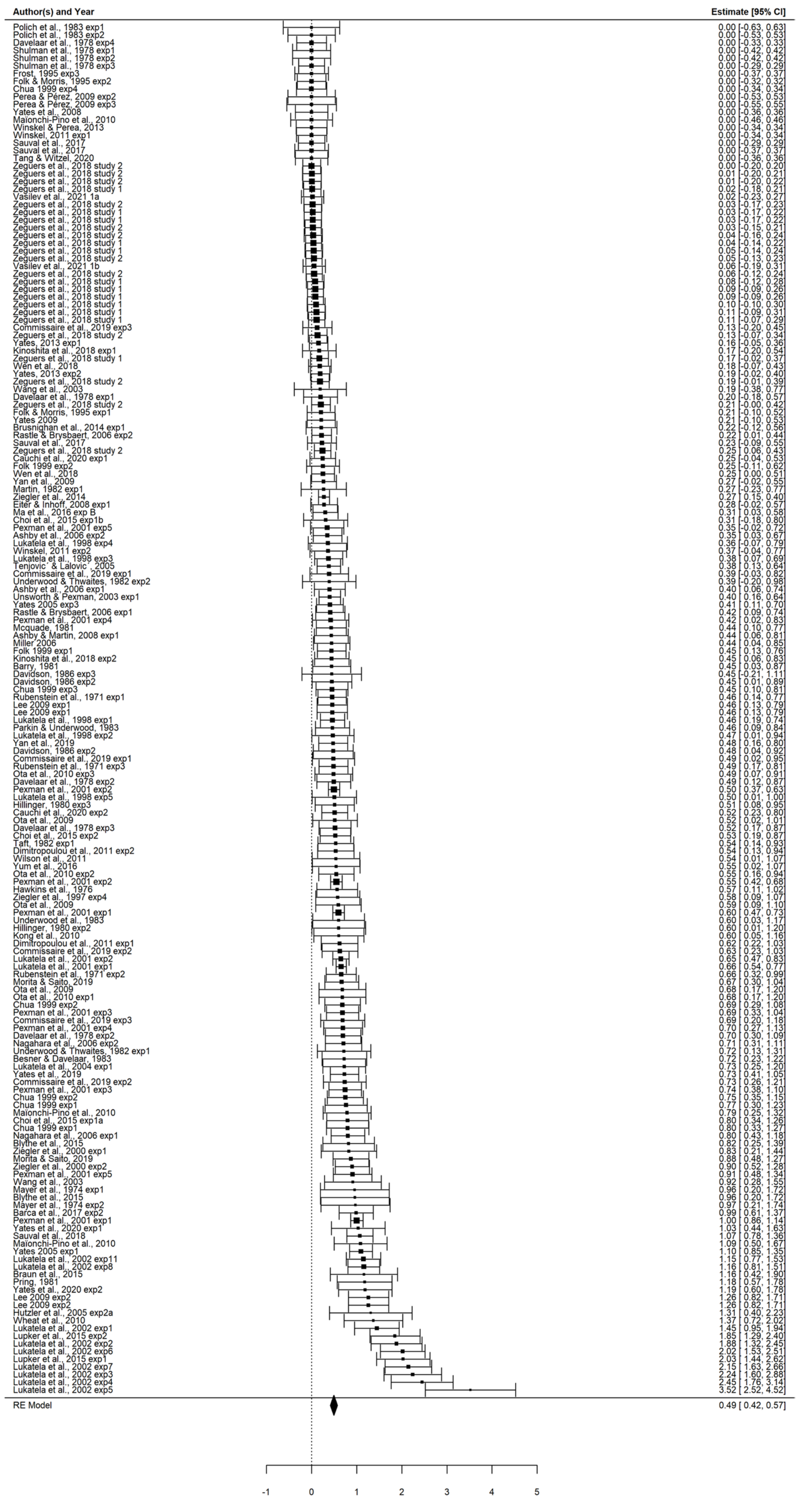


**Fig. 5** Forest plot of effect sizes for phonological effects on written word recognition

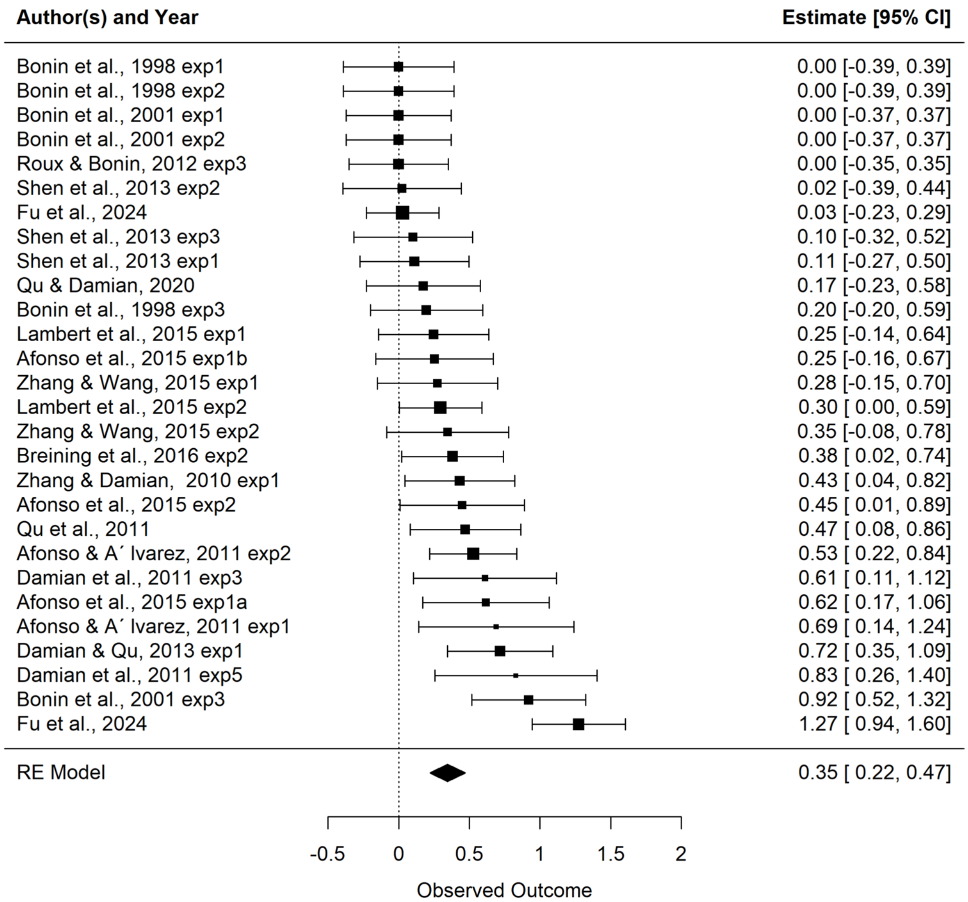


**Fig. 6** Forest plot of effect sizes for phonological effects on written word production

**Moderator analyses** As shown in Table 2, for the moderator *task*, significant phonological effects were found in all tasks except implicit priming, with a large effect in the Stroop task and smaller effects in the other tasks. For the moderator *alphabeticity*, the effect was significant for both alphabetic and non-alphabetic language, with no significant difference ($t = 0.69$, $p = .495$). For the moderator *orthographic depth*, effects were significant for all levels, with the smallest effect in 'substantially irregular' orthographies and the largest in 'relatively regular' orthographies, and the effects in these two types of orthographic systems were not significantly different ($t = -1.76$, $p = .090$). For the moderator *nativeness*, the effect was significant for both native and non-native speakers, with the effect numerically larger for non-native speakers but no significant difference ($t = 0.97$, $p = .340$).

## Discussion

The present study reports a comprehensive literature review on cross-modality effects in language tasks (orthographic effects on spoken word recognition and production, and phonological effects in word reading and writing). Results from four corresponding meta-analyses which included a large number of published studies revealed small- to-medium-sized but significant effects in all four language processing modalities. These results support a close coupling between orthography and phonology that is relevant in all modalities of language processing. The idea of a close coupling between orthography and phonology can be traced back to a foundational paper by Van Orden et al. (1990), which proposed that cross-talk occurs between orthographic and phonological representations during visual word processing. This view was later extended in the resonance framework of visual word recognition, positing that visual word recognition involves dynamic interactions between feedforward and feedback processes across orthographic and phonological levels (Stone et al., 1997). These theoretical insights underscore the coupling between orthography and phonology as a fundamental feature of language processing, which should be considered in future empirical studies and which should inform models of language processing.

What moderators affect orthographic or phonological effects? An important claim in the literature is that the size of the orthographic effect might depend on the nature of the task. For example, as highlighted in the Introduction, a possibility is that orthographic effects in spoken tasks will particularly clearly emerge in tasks which encourage strategic access to orthographic representations (such as auditory lexical decisions). Looking at the 'task' moderator analysis reported in Table 2, we are unable to see a clear pattern: as predicted, orthographic effects are substantial in auditory lexical decisions, but they are not much reduced in semantic judgements. The same holds for spoken word production, and written word recognition and production: effect sizes are to some extent variable dependent on task, but no clear pattern emerges which would indicate a role for 'strategic' access to cross-modal codes dependent on task. Overall, the moderator analysis suggests that cross-modality effects depend to some extent on the employed task, but that nonetheless they appear relatively consistently.

Two further potential moderator variables pertain to the orthographic properties of the target language. Alphabeticity refers to whether the target language used an alphabetic writing system, with the hypothesis that an alphabetic system, via substantial spelling-to-sound correspondences, would be more likely to generate cross-modality effects than a non-alphabetic system in which the mapping between spelling and sound is largely arbitrary. We found no evidence for this claim: in all four domains (listening, speaking, reading, writing) cross-modality effects did not statistically differ between alphabetic and non-alphabetic languages. A further analysis in which we specified orthographic depth by categorizing target language orthography as regular, reasonably regular, substantially irregular, and largely opaque also rendered unclear results. Again, the hypothesis was that the more orthographically transparent a language is, the stronger cross-modality effects should be, due to strong and systematic links between sound and spelling. However, numerically the opposite pattern was found in spoken word recognition, and in the other modalities (i.e., speaking, reading and writing) no systematic relationship between orthographic transparency/depth and the size of cross-modality effects emerged. We conclude that our results give no reason to believe that the extent of cross-modal activation depends on the properties of the target language orthography in any systematic way.

Finally, we explored the moderator nativeness. Because native languages are primarily learned in spoken format whereas non-native languages are typically acquired in both spoken and written form, the hypothesis is that cross-modality effects might be more pronounced in experiments with non-native compared to native speakers. This pattern was clearly found only in the studies on spoken production, where the effect for non-native speakers was almost triple as large as for native speakers. In the two orthographic tasks (reading and writing), the effects showed the same trend (numerically larger effects for non-native than for native speaker) but the comparison did not reach conventional significance. Overall, the moderator analysis suggests that the emergence of cross-modality effects depends to an important degree on the chosen task but that a division into 'strategic' and 'non-strategic' linguistic activities might not be appropriate. Further, cross-modality effects appear to be largely independent of the orthographic properties of a given target language. Cross-modality effect might be subject to whether individuals perform the activity in their native or non-native language.

It is acknowledged that the number of relevant studies for some of these analyses is very small (for instance, there is very limited research on phonological activation in non-native written word production) and this may have caused some of the statistical null findings in our moderator analyses; clearly more research is needed to render a more complete picture. Furthermore, despite the overall moderate effect sizes for cross-modality effects of the type investigated here, positive findings are mixed with a considerable number of null findings. Although we consider it unlikely that all positive findings can be attributed to 'strategic' factors (in the sense proposed by Cutler et al., 2010, for orthographic effects in phoneme detection), it is clear that additional moderators affect the conditions under which cross-modality effects are obtainable. Further research is needed to identify what these additional factors might be. One potential moderator pertains to the relative time course of within- and cross-modality activation. For instance, Rastle et al. (2011) observed that orthographic effects appear more pronounced in auditory lexical decisions than in shadowing (repeating aloud) and postulated that in speech-based activities phonological activation has primacy but orthographic activation lags behind. Shadowing can be carried out exclusively based on phonological activation whereas lexical decision requires processing at additional (higher) levels, hence providing the opportunity for orthographic effects to emerge. Whether an account which hinges on the relative time course of activation of spelling and sound can explain some of the inconsistencies in the empirical data regarding cross-modality effects remains to be seen.

As briefly alluded to in the *Introduction*, two scenarios have been proposed to account for cross-modality effects. A first possibility is that mental representations corresponding to orthographic and phonological systems are interlinked in the mind and brain such that whenever one system is accessed, the other is swiftly, automatically and transiently activated ('online' account). This type of account is generally compatible with neural assembly models of language which consolidate all elements of speech into a cohesive functional entity formed by interconnected neural populations (Pulvermüller, 1999; Strijkers, 2016a, b; Strijkers & Costa, 2016). In these models, language components have the potential to be activated synchronously or in close temporal proximity to each other. An alternative account of cross-modality effects is that a representational language system is permanently re-shaped via the presence of mental codes in the cross-modal domain ('offline' account). The latter possibility was specifically proposed to account for effects of literacy acquisition on spoken language processing (for an overview, see Kolinsky & Morais, 2018). Pattamadilok et al. (2022) describe this process as involving "…for instance, a reduction of the grain-size of phonological representations, a better specification of phoneme boundaries, a modulation of the activation threshold of spoken words or a transformation of phonological into 'phonographic' representations" (p. 1,543).

The online/offline distinction arose in the literature on speech processing. In spoken production, orthographic effects, to the extent that they have been found, are typically explained in terms of online accounts. For instance, Damian and Bowers (2003) suggested that the results of a series of reported experiments "provide some support for a strong non-modular approach in which non-relevant linguistic knowledge can be activated and feedback on relevant systems in order to constrain language processing" (p. 128). Similarly, Rastle et al. (2011) interpreted their results from a novel word learning task as reflecting "a highly interactive language system in which there is a rapid and automatic flow of activation in both directions between orthographic and phonological representations" (p. 1,542). However, offline explanations according to which literacy acquisition has shaped phonology are also worth considering, particularly under the assumption that the phonological system underlying speech perception and production is either identical, or separate but functionally linked (for discussion, see Martin & Saffran, 2002). For instance, certain empirical observations have been taken to support the psychological reality of the 'phoneme' in spoken production (Damian & Dumay, 2009; Qu et al., 2012). It is possible that mental representations corresponding to phonemes are the product of literacy acquisition (e.g., Morais, 2021) which leads to the interesting but to our knowledge to date untested prediction that in production tasks, phoneme-sized effects should be weaker or absent with illiterate speakers.

In the orthographic domain (reading and writing), a similar issue arises: as our review shows, orthographic tasks which do not require phonological retrieval exhibit phonological effects. Are these best explained via rapid 'online' co-activation of phonological codes, or is it possible that the nature of a given spoken language influences the structure and processing of the orthographic system? A standard assumption in visual word recognition is that orthographic input is rapidly re-coded into phonological format; indeed, early theories proposed that word identification is exclusively based on this phonological route (van Orden et al., 1988) and the idea of rapid access to phonology is a key component of classic 'triangle' PDP models of single word reading (e.g., Plaut et al., 1996). Given the wealth of evidence for phonological effects in various orthographic tasks (for instance, via the demonstration of pseudohomophone and masked phonological priming effects in LDT; e.g., Rastle & Brysbaert, 2006), we find it difficult to see how these could be explained other than via rapid and transient phonological co-activation (even in tasks which do not require spoken output). At the same time, orthographic systems almost certainly contain higher-order representations such as digraphs, graphemes, syllables, and morphemes (for overview, see Rapp & Fischer-Baum, 2014). Some of these representations are clearly the product of the spoken language which the orthography represents and therefore likely emerge from 'offline' shaping of orthography through phonological properties in mature readers' language.

In orthographic output tasks (writing, typing etc.) the typical assumption is again that 'online' transient cross-modal activation accounts for phonological effects. For instance, Bonin et al. (2001) explored phonological effects in written picture naming and stated that "the build-up of orthographic activation from pictures is phonologically constrained through the sequential operation of sublexical conversion" (p. 688). At the same time, it is possible that orthographic representations persistently incorporate phonological properties of the language that they represent. For instance, Kandel et al. (2009) found that orthographic rather than phonological syllable boundaries constrained handwriting of French third, fourth and fifth graders.

Overall, although our meta-analysis suggests that cross-modality effects are pervasive in both phonologically and orthographically based tasks, it is difficult to adjudicate between 'online' and 'offline' accounts and behavioural experiments alone are probably insufficient to advance this issue. Instead, neuroscientific evidence might provide clearer insight. It is beyond the remit of the present work to summarise this evidence, but to exemplify this approach, electrophysiology (EEG) provides insight into mental processes as they are carried out in the brain in response to stimulation. If a cross-modality effect were to have a relatively 'early' time signature, this might be taken to support the 'online' account which would predict fast and automatic cross-modal activation. Using this approach, Perre and Ziegler (2008) manipulated the orthographic consistency of spoken French words at an early or late position within the word. Event-related potentials showed prelexical and lexical effects of consistency, providing evidence in support of 'online' cross-modal activation of orthography. EEG studies of this type which explore the time course of activation of different types of codes have now been conducted in various domains (e.g., orthographic effects on spoken word language: Perre et al., 2009a, b; phonological effects on written word recognition:

Grainger & Holcomb, 2009; phonological effects on written word production: Qu & Damian, 2020).

A different approach towards establishing the functional role of cross-modality effects uses brain stimulation techniques. For instance, Pattamadilok et al. (2010) used transcranial magnetic stimulation (TMS) to explore the neural mechanism underlying orthographic effects on speech processing. Participants carried out an auditory lexical decision task and TMS was used to interfere with either phonological processing (by stimulating left supramarginal gyrus) or orthographic processing (by stimulating left ventral occipito-temporal cortex). A behavioural consistency effect was removed when stimulation was applied to the former but not the latter cortex, leading the authors to infer that the orthographic effect arose at a phonological rather than an orthographic level and hence favouring an 'offline' rather than an 'online' account of the effect.

Finally, neuropsychological studies of individuals with acquired brain damage might also provide relevant information. For instance, Rapp et al. (1997) documented a case of an individual with difficulties in lexical access in spoken and written output. The patient was asked to first write, and then pronounce, a series of simple line drawings, and generated a substantial proportion of trials on which the correct generation of a written response was followed by a semantic error in spoken production. Based on this pattern the authors rejected the 'phonological mediation' view according to which written output is produced via obligatory generation of spoken codes (see *Introduction*). Studies of this type have the potential to advance our understanding of the role and function of cross-modality activation in language processing.

In summary, our meta-analyses confirmed orthographic effects on spoken word recognition and production, and phonological effects on written word recognition and production. The underlying mechanism may be that orthographic and phonological representations are closely interconnected so that the flow of information is not constrained to one direction but is bidirectional, regardless of whether it is spoken or written word processing. Furthermore, our analyses suggest that the strength of cross-activation effects is influenced by experimental tasks and perhaps by nativeness of languages.

**Authors'contributions** **Xiaohui Cui**: Writing – original draft; methodology; data curation; formal analysis. **Markus F. Damian:** Supervision; writing – review and editing. **Qingqing Qu**: Conceptualization; methodology; writing – original draft, writing – review and editing, supervision, funding acquisition.

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**Availability of data and materials** All the study information and data for analysis are publicly available at the Open Science Framework website: https://osf.io/bkdj5/.

**Code availability** The analysis R code script is publicly available at the Open Science Framework website: https://osf.io/bkdj5/.

## Declarations

**Competing interests** The authors have no competing interests to declare that are relevant to the content of this article.

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

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