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When underadditivity of factor effects in the Psychological Refractory Period paradigm implies a bottleneck: Evidence from psycholinguistics

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The Psychological Refractory Period (PRP) paradigm is a dual-task procedure that can be used to examine the resource demands of specific cognitive processes. Inferences about the underlying processes are typically based on performance in the second of two speeded tasks. If the effect of a factor manipulated in Task 2 decreases as the stimulus onset asynchrony (SOA) between tasks decreases (*underadditivity*), the normative inference is that the effect of this factor occurs prior to a limited-capacity central processing mechanism. In contrast, if the effect of a factor is additive with SOA then the inference is that this indexes a process that either uses a limited-capacity central processing mechanism or occurs after some process that uses this mechanism. A heretofore unidentified exception to this logic arises when Task 2 involves two separate processes that operate in parallel, but compete. Interference with one process in Task 2 because of work on Task 1 will eliminate or reduce competition within Task 2 and is hence manifest as an underadditive interaction with decreasing SOA. This is illustrated here by reference to a PRP experiment in which the ubiquitous effect of spelling-to-sound regularity on reading aloud time is eliminated at a short SOA and by consideration of three converging lines of investigation in the PRP paradigm when Task 2 involves reading aloud.

Keywords: Visual word recognition; Psychological Refractory Period paradigm; Lexical processing; Nonlexical processing; Automaticity.

It is typically the case that, over time, most paradigms in cognitive psychology come to be associated with a normative interpretation of results that are commonly observed. Investigators typically adopt this normative interpretation when using the paradigm to investigate a variety of subsequently arising questions. Often, over a period of time, enough anomalies accumulate that the normative interpretation has to be modified, discarded, or understood to only hold under certain

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circumstances. The central point of the present paper is that the normative interpretation of a particular outcome in the context of the Psychological Refractory Period paradigm (hereafter PRP) is, under certain circumstances, unlikely to be correct, and that a different interpretation, provided here, should be preferred.

The PRP paradigm

Participants in the PRP paradigm typically perform two tasks in response to sequentially presented stimuli (S1 and S2) with the instruction to give priority to Task 1 (S1) and to respond to Task 1 before responding to Task 2. Under these conditions reaction time (RT) to S2 increases substantially as the stimulus onset asynchrony (SOA) between S1 and S2 decreases. This PRP effect was first reported quite some time ago and was attributed to a mechanism that could only operate on one task at a time (see Welford, 1952). More recently, Pashler (1984; see also Pashler's, 1994, review) developed a seminal analysis of performance in this paradigm that has had a major impact on how researchers think about the resource demands of mental processing. Indeed, psycholinguists have begun to use this dual-task methodology in order to address fundamental questions about visual and auditory word recognition and speech production (e.g., Cleland, Gaskell, Quinlan, & Tamminen, 2006; Dell'Acqua, Job, Peressotti, & Pascali, 2007; Ferreira & Pashler, 2002; McCann, Remington, & Van Selst, 2000; O'Malley, Reynolds, Stolz, & Besner, 2008; Rabovsky, Alvarez, Hohlfeld, & Sommer, 2008; Reynolds & Besner, 2006).

Cognitive slack logic

According to the "cognitive slack" logic used by Pashler, the need for the same limited-capacity process (hereafter referred to as *central attention* following Johnston, McCann, & Remington, 1995) by both tasks has straightforward consequences for Task 2 processes that occur before, during, or after this bottleneck. For example, when Task 1 and Task 2 overlap temporally, and participants are instructed to respond to Task 1 before Task 2, Task 1 typically gains access to central attention before Task 2 (see Figures 1 and 2). Task 2 processes that require central attention are therefore functionally postponed until it becomes available. If the effect of a factor manipulated in Task 2 occurs prior to the processing bottleneck, the effect of this factor will be absorbed into the slack created by other Task 2 processes waiting for central attention to become available. That is, a factor that affects processing prior to central attention will produce no RT cost at the short SOA because it makes no use of central attention. This pattern is commonly described as "underadditive" (of a factor in combination with decreasing SOA: The effect is smaller or absent at the shorter SOA than at a long SOA).

In contrast, if a factor manipulated in Task 2 has additive effects on RT with SOA, then this factor affects a process that either (a) uses central attention or (b) occurs after central attention. If prior processing does not use central attention, then the factor manipulated in Task 2 is assumed to index a process that uses central attention.

This logic is the normative interpretation of underadditivity and additivity of factor effects in combination with decreasing SOA in the PRP paradigm (Pashler, 1984, 1994). Theoretical variants exist in which some processes share capacity between Tasks 1 and 2 rather than an all-or-none bottleneck (Navon & Miller, 2002; Tombu & Jolicouer, 2003), but the central inference in which underadditivity implies capacity free processing still applies (i.e., no interference from Task 1).

A novel case: When an underadditive interaction implies a bottleneck

There is, however, a heretofore unidentified case when underadditivity of a factor effect with decreasing SOA in Task 2 can be understood as reflecting reduced competition between component processes within Task 2 because one of the processes is bottlenecked by Task 1. Here, Task 2 involves a pair of separate processes that overlap in time and, at one level of a factor, compete with one another, despite the fact that a

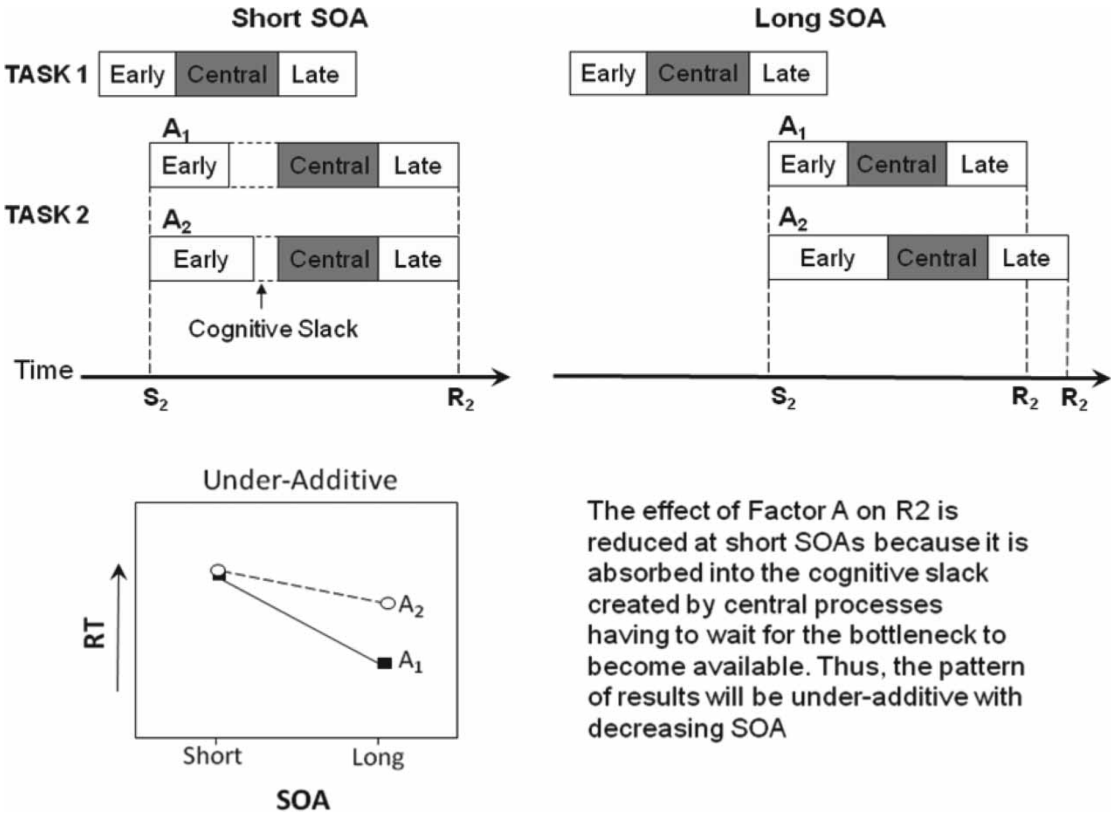

Figure 1. *The normative account of an underadditive interaction with stimulus onset asynchrony (SOA) in the Psychological Refractory Period (PRP) paradigm using cognitive slack logic. Processes arising before central attention are labelled as "early", those requiring central attention are labelled "central" and shaded, processes that occur after central attention are labelled as "late". Cognitive slack is indicated using dotted lines.* S_2 *refers to the presentation of the stimuli for Task 2;* R_2 *refers to the response to Task 2.*

correct response is driven by only one of these two processes. If processing in Task 1 delays one of the processes in Task 2 (one that competes but does not drive a correct response) but not the other (or at least less so), this will reduce the competition between the two processes as SOA decreases. *In this instance underadditivity of a factor with decreasing SOA arises because Task 1 interferes with a component process in Task 2, rather than reflecting interference-free processing in Task 2.*

In order to illustrate this novel case of underadditivity with a concrete example (and experiment) we first consider a highly successful computational account of reading aloud (Coltheart and colleagues' dual-route cascaded model). We then consider the results of some experiments on reading aloud in the context of the PRP paradigm. Finally, we consider the well-established spelling–sound regularity effect in reading aloud, and we derive the a priori prediction that the effect of this manipulation when reading aloud in the context of the PRP paradigm will be underadditive with decreasing SOA in Task 2, because one of two processes is bottlenecked.

Reading aloud: The Dual-Route Cascaded model

One major account of reading aloud is provided by Coltheart, Rastle, Perry, Langdon, and Ziegler (2001) in the context of their implemented Dual-Route Cascaded model (DRC). This model

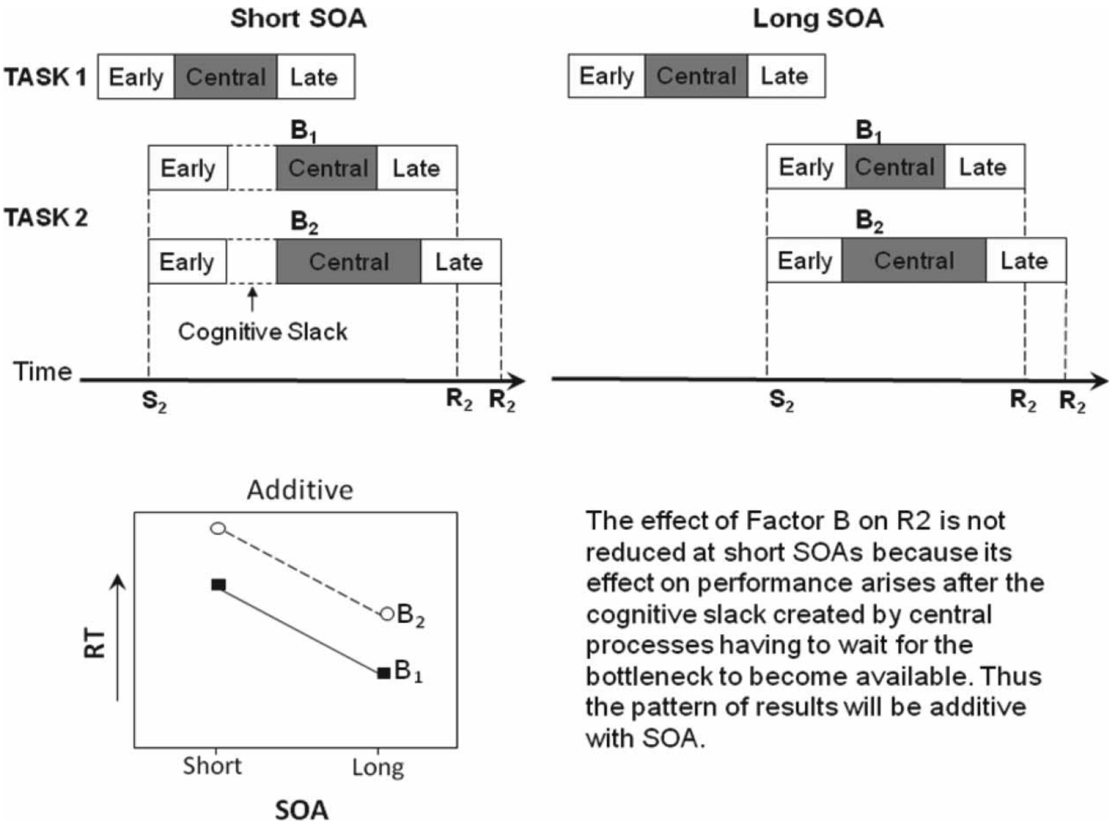

Figure 2. *The normative account of additive effects with stimulus onset asynchrony (SOA) in the Psychological Refractory Period (PRP) paradigm using cognitive slack logic. Processes arising before central attention are labelled as "early", those requiring central attention are labelled "central" and shaded, processes that occur after central attention are labelled as "late". Cognitive slack is indicated using dotted lines.* S_2 *refers to the presentation of the stimuli for Task 2;* R_2 *refers to the response to Task 2.*

generates a phonological code from print by recourse to lexical and nonlexical routines. The DRC model (see Figure 3) has been remarkably successful at simulating a wide variety of phenomena (as has the related CDP+ model by Perry, Ziegler, & Zorzi, 2007). For present purposes we treat these models as equivalent (though it should be noted that the nonlexical route in the latter model differs from the DRC model in that it can account for one phenomenon—consistency—that the DRC model cannot simulate in its present form).

When reading aloud, the lexical route generates a phonological code via activation of the orthographic lexicon, which in turn activates the phonological lexicon. Each lexicon contains a single node for each unique word the model knows (spelled in the orthographic lexicon; sounded in the phonological lexicon). Activation from the phonological lexicon feeds forward to the phoneme system and back to the orthographic lexicon. The lexical route can read aloud all the words it knows and is required to correctly read aloud words that do not follow the typical spelling-to-sound rules (exception words such as *pint*).

When reading aloud, the nonlexical route translates print into sound sublexically via a set of grapheme–phoneme correspondence rules applied left to right, one letter at a time. This route produces a correct pronunciation for words

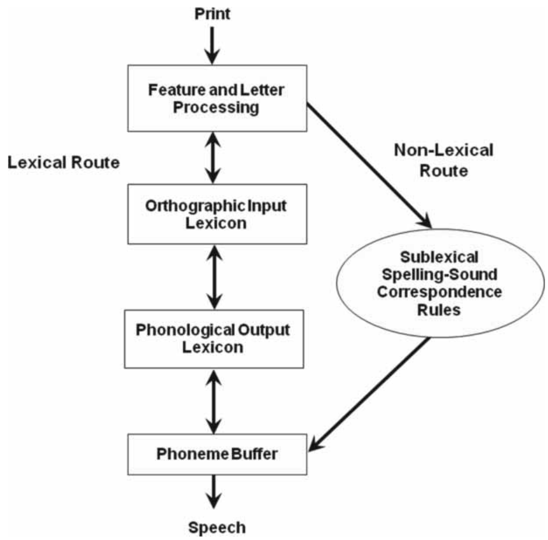

Figure 3. *The Dual-Route Cascaded model (DRC) architecture.*

that follow typical spelling-to-sound rules (regular words such as *mint*) and is required to read nonwords aloud (e.g., *fint*). The nonlexical route generates a regularized pronunciation in response to exception words (e.g., "pint" is pronounced such that it rhymes with "mint").

The PRP paradigm and reading aloud

There are a number of experiments in which reading aloud has been investigated in the context of the PRP paradigm. When reading aloud is Task 2, it is possible to investigate which processes use central attention (or follow a process that uses central attention) and which processes do not use central attention (in all experiments discussed here, Task 1 was tone identification). We start by considering sublexical spelling-to-sound conversion.

Sublexical spelling-to-sound conversion

According to the DRC account, only the sublexical routine can read nonwords aloud correctly. As noted earlier, the sublexical conversion of print to sound operates serially left to right across each letter in the string, and an utterance only starts when all the letters in the string have been converted to phonology. Thus, the more letters in the string, the longer it takes to read aloud a nonword (e.g., see Besner & Roberts, 2003; Weekes, 1997). When reading nonwords aloud in Task 2 in the PRP paradigm, nonword letter length and SOA have additive effects on RT (see Reynolds & Besner, 2006, for two such demonstrations). Application of the standard interpretation of additive effects in the context of the PRP paradigm à la Pashler therefore implies that Task 1 bottlenecks the sublexical conversion of print to sound, or a prior process.

A second example of sublexical processing involves the "whammy" effect (Rastle & Coltheart, 1998). The nonlexical routine translates letters into phonemes in left-to-right fashion. This leads to the pronunciation of some phonemes encountered earlier in the string (left to right) having to be modified (a time-consuming process) because of a later translation (e.g., the "h" in "steth" modifies how the second "t" is pronounced whereas the "k" in "stelk" does not modify how the "l" is pronounced). It therefore takes longer to read aloud an item like "steth" correctly than an item like "stelk" despite the fact that nonword letter length is held constant across the two conditions. When reading nonwords aloud in Task 2 of the PRP paradigm, Reynolds and Besner (2006) reported that the whammy effect and SOA have additive effects on RT. Application of the standard interpretation of additive effects in the context of the PRP paradigm à la Pashler therefore implies that Task 1 again bottlenecks the sublexical conversion of print to sound, or a prior process.

A third example of sublexical processing involves repetition priming when reading aloud. Letter strings like BRANE (called pseudohomophones because they sound identical to real words but do not spell real words) have a lexical entry in the phonological output lexicon (the phonology associated with BRAIN) but do not have a lexical entry in the orthographic input lexicon. The only way to fully activate the lexical entry in the phonological output lexicon for an item like BRANE when reading aloud is via preliminary sublexical translation of spelling to sound (see Figure 2). O'Malley et al. (2008) reported that, when reading aloud, repetition priming for such pseudohomophones (when the first and second presentations were separated by 150 items) was additive with SOA in the context of the PRP paradigm. Application of the standard interpretation of additive effects in the context of the PRP paradigm à la Pashler therefore implies that Task 1 again bottlenecks the sublexical conversion of print to sound, or a prior process.

In summary, when reading aloud, all the published experimental manipulations that involve sublexical spelling-to-sound translation in the context of the PRP paradigm have yielded additive effects of that factor and SOA. Given Pashler's interpretation of additive effects, these results imply that Task 1 bottlenecks the sublexical conversion of print to sound, or some prior process(es). We turn now to a consideration of how lexical processing behaves in the context of the PRP paradigm.

Lexical processing

Exception words such as "pint", in the context of Coltheart and colleagues' DRC model, can only be read aloud correctly via the lexical route. Both Reynolds and Besner (2006) and O'Malley et al. (2008) report experiments in which, when reading aloud, repetition priming for exception words (when repetitions are separated by an average of 150 items) was significantly smaller at the short SOA than at the long SOA in the context of the PRP paradigm (that is, the effect of repetition for words was underadditive with decreasing SOA). It is implausible that there is persisting activation of feature and letter level processing over such a long lag given that individual letters and features are repeated numerous times throughout the experiment. Repetition priming in this context must therefore reflect persisting change (learning) at the lexical level in the context of the DRC framework (Morton, 1969, suggested that the response threshold gets reduced with repetition; the fact that repetition interacts with word frequency such that low-frequency words benefit more than high-frequency ones [e.g., see Visser & Besner, 2001] converges on the idea that repetition has a lexical locus). Pashlerian logic as applied to the interpretation of this underadditive interaction therefore implies that not only is processing occurring along the lexical route during Task 1 processing, but that prior processing (feature and letter level) must also take place without interference from Task 1. If this was not the case (i.e., if feature- and letter-level processing needed central attention) then repetition and SOA would have yielded additivity rather than underadditivity.

By way of summary then, all of the results described above provide a strong case for the assertion that, when reading aloud in Task 2, sublexical spelling-to-sound conversion (the nonlexical route as seen in Figure 2) is bottlenecked by Task 1. In contrast, at least some processing along the lexical route can occur in parallel with Task 1 given that repetition priming for words is underadditive with decreasing SOA.

In all the experiments described above, either participants read nonwords aloud, and the experimental factor that was manipulated indexed the operation of the nonlexical route, or participants read words aloud, and the manipulated factor indexed the operation of the lexical route. We now turn to the situation in which participants read words aloud, but the experimental manipulation indexes the extent to which sublexical processing interferes with lexical processing.

The regularity effect in reading aloud

Printed English is notoriously difficult to learn to read aloud because the same spelling pattern is often associated with more than one pronunciation, and these exceptions must be learned on an individual basis. Indeed, even skilled university-level readers are slower to read aloud words like "pint" and "have" because they are exceptions to the typical relation between spelling and sound in which _INT is pronounced as in "mint", and _AVE is pronounced as in "cave" (e.g., Roberts, Rastle, Coltheart, & Besner, 2003).

In the DRC framework this "regularity" effect (slower reading aloud of exception words than regular words) is explained in terms of competition at the phoneme level. A single phoneme inhibits all other phonemes at the same position. Thus, the nonlexical and lexical routes activate different phonemes in the case of an exception word, and it takes time to resolve the competition, leading to slower RTs than those for regular words where both routines activate the same set of phonemes.[1]

Standing cognitive slack logic on its head

How then will the regularity effect play out when reading aloud in Task 2 in the PRP paradigm (where Task 1 is tone identification as it has been in all of the relevant experiments discussed here)? If the earliest point in Task 2 where processing is delayed by Task 1 is common to lexical and nonlexical routes (i.e., feature and letter identification) then additive effects of regularity and SOA on RT should be observed because the regularity effect is subserved by processes that occur after the bottleneck. However, as we noted earlier, the effect of long lag repetition (faster responses to repeated words after 150 intervening items) when reading aloud in Task 2 is underadditive with decreasing SOA in the PRP paradigm (O'Malley et al., 2008; Reynolds & Besner, 2006). This implies that both feature and letter processing, as well as later processing (i.e., at least some lexical processing) can be carried out in parallel with Task 1 on the (unchallenged) assumption that the source of this repetition effect lies well beyond the feature and letter levels.

If sublexical spelling-to-sound conversion in Task 2 is bottlenecked by tone detection in Task 1 then the basis for competition with the lexical route is eliminated (or at least reduced, depending on how much delay the nonlexical route suffers relative to the lexical route). On this scenario, the regularity effect should be underadditive with decreasing SOA because there is less interference between lexical and nonlexical routines at a short SOA than at a long one. That is, this instance of underadditivity arises because of a bottleneck in Task 2 that is specific to sublexical spelling–sound conversion. To repeat: There are strong grounds for the a priori prediction that, when reading aloud in Task 2, regularity and SOA will be underadditive with decreasing SOA *despite sublexical processing being bottlenecked by Task 1.*

Method

Participants

A total of 40 undergraduate students from Trent University participated for course credit. All individuals had normal or corrected-to-normal vision and were native English speakers.

Stimuli

The 100 irregular words (mean occurrence per million words of text = 5.2) had a mean orthographic neighbourhood size of 3.2 and ranged in

[1] A reviewer of a previous version of this manuscript requested that we consider single-route models in this context. Our reply is that we are unaware of anyone who currently holds the view that an average group of university-level readers operates like a single-route model (e.g., as in the implemented model of Seidenberg & McClelland, 1989). Even those who are strong advocates of PDP models (see Plaut, McClelland, Seidenberg, & Patterson, 1996) prefer versions that are "dual route" (note that these dual-route models are very different from dual-route localist models such as DRC, or hybrid models such as CDP +). That said, we also hold the view that dual-route PDP models currently on the table are consistent with the results of the present experiment as well as with those of previous experiments (as in O'Malley et al., 2008; Reynolds & Besner, 2006). That is, one route (the direct orthography to phonology route) correctly reads aloud nonwords, regular words, and high-frequency exception words, but never learns the correct mappings for low-frequency exception words according to the division of labour hypothesis advanced by Plaut and colleagues. This route is bottlenecked by Task 1. The other route (orthography to semantics to phonology) is typically used to correctly read aloud low-frequency exception words. Competition between these routes normally produces the regularity effect, but in the context of the PRP paradigm the nonsemantic route is bottlenecked by Task 1 whereas reading via semantics is not bottlenecked. Hence, when the former route is bottlenecked the latter route will escape the interference from the former route in the case of low-frequency exception words (and regular words will also now be read via the semantic route).

length from 4–6 letters (mean = 4.6). The stimulus set can be seen in the Appendix. The position of irregularity was in the first or second phoneme for all irregular words. The 100 regular words had similar characteristics with a mean frequency of 5.2 and a mean orthographic neighbourhood size of 3.1, and they also ranged in length from 4–6 letters (mean = 4.6).

In order to verify that the two sets of words were matched for lexical characteristics the stimuli were run through both DRC and CDP+ models with the nonlexical route turned off. Responses are thereby completely determined by feature and letter processing and the lexical route. Three of the words either were not in DRC's lexicon (peon) or were outliers (mould and moult yielded responses greater than 3 standard deviations from the mean) and were therefore removed from all analyses. The model took an average of 77.7 cycles to read the regular words and 77.9 cycles to read the exception words ($t < 1$). For CDP+, "peon", "mould", "moult", and "gauge" were all absent from the lexicon. CDP+ took an average of 126.4 cycles to read regular words and 128.1 cycles to read exception words ($t < 1$).

Apparatus

Stimulus presentation was controlled by an IBM T42 laptop running E-Prime 1.2 (Schneider, Eschman, & Zuccolotto, 2002). Responses were collected using a PST microphone and response box assembly.

Procedure

Items were counterbalanced across the SOA conditions. The order of SOAs within the single block of trials was also randomized anew for each participant. Participants were assigned to one of the counterbalance conditions based on the order in which they came to the laboratory. Participants were tested individually and were seated approximately 50 cm from the computer monitor.

Each trial began with a cross (+) displayed at the centre of the screen. Participants were instructed to fixate on the cross and to press the spacebar to initiate the trial. When the spacebar was pressed a blank screen replaced the fixation screen. After 500 ms either a high (1500 Hz) or a low (500 Hz) tone sounded for 50 ms. Participants responded to the tone task by pressing one of two buttons on the PST response box. Either 50 ms or 1,500 ms after the onset of the tone, a word was presented on the computer screen, centred horizontally at fixation. Stimuli were presented in 18-point, lower-case Courier New font. The word remained on the screen until it was read aloud into the microphone. Participants were instructed to perform both tasks as quickly and accurately as possible, but to respond to the tone task first. Responses (correct/error/spoiled) were coded by an experimenter in the room when the experiment was conducted.

Results

Mean RTs and percentage errors for each condition can be seen in Table 1. If on any trial an error was made in either Task 1 or Task 2 then the RT was discarded from both tasks. This resulted in the removal of 3.5% of the RT data

Table 1. *Mean reaction times and mean percentage errors at short and long stimulus onset asynchronies in Tasks 1 and 2*

	SOA			
	Short (50 ms)		*Long (1,500 ms)*	
	RT	*%E*	*RT*	*%E*
Task 1:				
Tone identification				
Irregular words	565	4.6	554	2.6
Regular words	571	4.7	560	3.2
Difference	− 6	− 0.1	− 6	− 0.6
Task 2:				
Reading aloud				
Irregular words	1,001	7.4	636	8.9
Regular words	989	1.9	598	2.9
Difference	12	5.5	38	6.0

Note: SOA = stimulus onset asynchrony. RT = reaction time in ms. %E = percentage errors.

due to errors in Task 1 and an additional 4.4% of the RT data due to errors in Task 2. An additional 2.4% of the data were considered spoiled due to response grouping of Task 1 responses with Task 2 (RTs to Task 1 > 2,500 ms) or voice key errors in Task 2 and were therefore also removed. The remaining correct RTs for each participant were submitted to a trimming procedure in which scores greater than 2.5 standard deviations from a cell mean were treated as outliers. This resulted in the removal of 5.0% of the correct RT data in Task 1 and an additional 2.0% of the correct RT data in Task 2. As in prior work (e.g., Reynolds & Besner, 2004, 2006) the item data were *z*-scored prior to the analysis to reduce the impact of individual subject variance. The *z*-scores were calculated by collapsing across all conditions.

Task 1: Tone discrimination

Analysis of the RT data revealed a marginal main effect of SOA in which RTs were 10 ms slower at the short SOA, $F_1(1, 39) = 3.0$, $p < .10$, $MSE = 1{,}532$; $F_2(1, 198) = 5.9$, $p < .05$, $MSE = .063$. More errors were observed at the short SOA, $F_1(1, 39) = 9.6$, $p < .01$, $MSE = 12.5$; $F_2(1, 198) = 15.4$, $p < .001$, $MSE = 13.2$. No other effects approached significance in either the RT or the error analysis (Fs < 1).

Task 2: Reading aloud

Analysis of the RT data yielded the standard finding that as SOA decreased, RT increased, $F_1(1, 39) = 298.5$, $p < .001$, $MSE = 19{,}125$; $F_2(1, 198) = 4{,}994.2$, $p < .001$, $MSE = 0.038$. A main effect of regularity was also observed (faster responses were made to regular words), $F_1(1, 39) = 12.8$, $p < .001$, $MSE = 1{,}938$; $F_2(1, 198) = 14.4$, $p < .001$, $MSE = 0.075$. Critically, there was an underadditive interaction between decreasing SOA and regularity in which the regularity effect was smaller at the short SOA, $F_1(1, 39) = 8.2$, $p < .01$, $MSE = 865$; $F_2(1, 198) = 10.4$, $p < .05$, $MSE = 0.038$. The effect of regularity at the short SOA was not significant, $t_1(39) = 1.2$, $p > .10$; $t_2(198) < 1$.

Analysis of the error data revealed that as SOA decreased, errors decreased, $F_1(1, 39) = 8.5$, $p < .01$, $MSE = 7.3$; $F_2(1, 198) = 6.6$, $p < .05$, $MSE = 14.3$. Fewer errors were made to regular words than to irregular words, $F_1(1, 39) = 52.3$, $p < .001$, $MSE = 25.2$; $F_2(1, 198) = 34.4$, $p < .001$, $MSE = 70.4$. There was no interaction between SOA and regularity ($F < 1$).

Discussion

The standard regularity effect for RTs is observed at the long SOA (it takes more time to start to read aloud exception words than regular words) but it is significantly smaller (and nonsignificant) at the short SOA.[2] The regularity effect in the error data was not reduced at the short SOA relative to the long SOA. This is attributable to many university-level readers simply not knowing the correct spelling for some of these low-frequency exception words (and hence lacking an entry in the orthographic input lexicon) or not knowing the word at all (and hence lacking a lexical entry in both the orthographic input lexicon and the phonological output lexicon).[3] Thus, participants who do not know an exception word for either of the above reasons can only pronounce it incorrectly by reference to the nonlexical route (simply later at the short SOA due to that route being delayed) resulting in the observed additivity in the error data (i.e., the same size regularity effect across SOA). Note that if a participant does not have a lexical representation for a regular word for any of the above reasons it does not matter

[2] It should be acknowledged that Task 1 performance is slightly slower and significantly more error prone at the short than at the long SOA. This suggests some capacity sharing between Tasks 1 and 2 but does not undermine the general conclusion given that this capacity sharing is not affected by word type.

[3] In a follow-up survey of a third-year undergraduate class at Waterloo (which we infer typically has better readers than at Trent, based on admitting grade averages) we found that more than 50% of the students did not recognize the exception words “joule”, “scythe”, “lieu”, “lathe”, and “lithe”.

because such words are always read aloud correctly by the nonlexical route.

Given the three findings discussed at length in the introduction—that is, (a) the nonword letter length effect is additive with SOA in the PRP paradigm, (b) the whammy effect is additive with SOA in the PRP paradigm, and (c) the repetition effect for pseudohomophones is additive with SOA in the PRP paradigm—the simplest conclusion is that sublexical spelling-to-sound conversion is bottlenecked in the context of the PRP paradigm. Therefore, the underadditive interaction between regularity and SOA as seen here in the RT data is most parsimoniously understood as again reflecting a bottleneck in sublexical processing in Task 2 due to Task 1 processing. This bottleneck allows the lexical process to proceed without interference from the sublexical process at the short SOA, and, hence, no regularity effect is seen at the short SOA in RT. This bottlenecking interpretation of underadditivity in the context of the PRP paradigm is therefore novel and represents an exception to the normative interpretation in which an underadditivity with decreasing SOA is taken as evidence that parallel processing between Tasks 1 and 2 occurs.[4]

The normative interpretation

Given the conservative nature of science it is natural that at least some researchers will persist in wanting to argue for the normative interpretation of the present results. That is, the underadditive interaction between regularity and decreasing SOA on RTs reported here reflects reading aloud being able to proceed without interference from Task 1, at least to the level at which regularity affects processing. The central problem with this argument is that it needs to assume that sublexical spelling to sound is not bottlenecked by Task 1. However, in the introduction we reviewed multiple reports that different ways of indexing the use of the sublexical routine (i.e., nonword letter length, whammies, and repetition priming for pseudohomophones) all yield additive effects on RT in conjunction with SOA in the context of the PRP paradigm. These results have all been interpreted as evidence that sublexical processing is bottlenecked by Task 1. To simply ignore such results strikes us as ill advised.[5,6]

[4] It has not escaped our attention that the results observed here bear some resemblance to those reported by Paap and Noel (1991). They reported that carrying a large memory load facilitated the reading aloud of exception words, and they argued that this occurred because the memory load interfered with the operation of the nonlexical route, but not the lexical route. The Paap and Noel result has been the subject of numerous investigations, almost of all of which have failed to replicate the original result. However, Hayes and Masterson (2002) report that individual differences play a strong role in this context and that it is possible to replicate the Paap and Noel result when the appropriate level of reader skill is considered. Despite the similarities between the present arguments and those of Paap and Noel, and Hayes and Masterson, it should be noted that the Paap and Noel paradigm does not involve speeded responses to two different tasks, nor a prior response to the memory load before reading aloud, and that in their paradigm participants carry a large memory load of digits, whereas in the present paradigm there is no memory load to speak of. More generally, although the Paap and Noel paradigm is "dual task" it is not of the PRP variety and therefore does not permit any straightforward inferences as to how processing unfolds in the context of the latter paradigm.

[5] An anonymous reviewer for a different journal argued that the interpretation of underadditivity of repetition priming and SOA reported by Reynolds and Besner (2006) and O'Malley et al. (2008) is somehow compromised because in the Stroop task a small set of items are repeated numerous times yet Fagot and Pashler (1992) reported that the Stroop effect and SOA had additive effects in the PRP paradigm. We agree that the Fagot and Pashler results ultimately need to be reconciled with those from the experiments by Reynolds and Besner and O'Malley and colleagues, but comparison of these different kinds of experiments is not straightforward. For example, given that there are numerous repetitions of Stroop stimuli in the Fagot and Pashler experiment it might be the case that the first repetition in their experiment would yield an underadditive interaction with SOA. Later repetitions might reflect a different form of retrieval (e.g., something more akin to explicit memory as in Carrier & Pashler, 1995, where timed old/new judgments were also additive with decreasing SOA in the PRP paradigm). A different point is that both words and colours are repeated in Fagot and Pashler's PRP experiment. If repetition benefits both words and colours to the same extent then we do not see the basis for expecting underadditivity in their experiment.

[6] The reviewer referred to earlier (see Footnote 5) also argued that McCann et al.'s (2000) report that word frequency and SOA are additive factors in the context of PRP is also at odds with the reports that word repetition and SOA yield an underadditive

Another way to avoid giving up the normative interpretation of underadditivity in the present context is to suppose that the effect of regularity should be explained in some way other than that considered here (i.e., that it does not reflect competition between lexical and sublexical routines in the context of accounts like DRC and CDP+ or, in the case of PDP models, competition between the orthography to semantics to phonology route on the one hand and the orthography to phonology route on the other hand). This approach has the problem that the experimental and theoretical literature on the regularity effect is both broad and deep (e.g., see Coltheart et al., 2001; Perry et al., 2007). Whatever this alternative explanation is, it will need to be shown that it is consistent with all the data accumulated over the last 30 years or so from intact university level readers, from patients with acquired surface dyslexia, as well as from children with developmental surface dyslexia. This seems a formidable challenge, but of course there is no reason that someone so inclined should not attempt to develop such an account. However, until such an account is worked out in detail and presented formally (i.e., in a refereed publication) we prefer to work with the explanation that, to date, has stood the test of various competing accounts (e.g., see Roberts et al., 2003).

CONCLUSIONS

The central point of the present work is that underadditivity of a factor effect with decreasing SOA in the context of the PRP paradigm can sometimes be understood in a nonstandard way. That is, rather than reflecting interference-free processing across Tasks 1 and 2, it can also be understood in terms of a bottleneck that affects one of two parallel processes in Task 2. To put it another way, the observation of underadditivity of a factor effect as SOA decreases does not unambiguously identify situations in which component processes can operate in parallel across Tasks 1 and 2. More generally, the present analysis is important in that the use of the PRP paradigm is likely to expand to other domains, and dual-process accounts are the rule rather than the exception in cognitive psychology, cognitive science, and cognitive neuroscience.

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interaction in the context of the PRP paradigm. In response, we note that a closer look at the McCann et al. data shows that, across experiments, there is evidence for an underadditive interaction (this point has been explicitly made by Reynolds & Besner, 2006) and that there are numerous other reports of an underadditive interaction between word frequency and SOA in the context of the PRP paradigm (see Cleland et al., 2006; most recently, see Rabovsky et al., 2008). We therefore do not yet understand the basis for the putative contradiction that this reviewer argues for (and, of course, if both lexical and non-lexical processes were bottlenecked to the same extent, the present results could not occur).

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APPENDIX

Items used in the experiment

Regular words			*Exception words*		
aide	*haul*	*stump*	*ache*	*isle*	*thee*
boost	*helm*	*surge*	*bald*	*jolt*	*thence*
brag	*leaf*	*sway*	*balm*	*joule*	*thief*
brew	*limp*	*swig*	*baste*	*knoll*	*thou*
brisk	*lurk*	*swine*	*bathe*	*lathe*	*tomb*
chant	*lute*	*swipe*	*beau*	*leapt*	*vase*
charm	*merge*	*swoop*	*buoy*	*lieu*	*volt*
cling	*mesh*	*tenth*	*cask*	*lithe*	*waltz*
clump	*midst*	*thorn*	*chaise*	*luge*	*wand*
coax	*mirth*	*toad*	*chaste*	*malt*	*warm*
coin	*moan*	*troop*	*chef*	*mauve*	*warp*
crawl	*notch*	*tune*	*chic*	*monk*	*wasp*
craze	*oath*	*twin*	*chord*	*mould*	*weird*
crib	*plea*	*vamp*	*chrome*	*moult*	*whilst*
crumb	*plod*	*wedge*	*chute*	*mousse*	*wield*
crypt	*plum*	*whim*	*colt*	*ninth*	*wolf*
cube	*pout*	*wrap*	*comb*	*palm*	*womb*
ditch	*reef*	*wreck*	*cough*	*paste*	*worm*
drake	*reign*	*yawn*	*daft*	*pearl*	*yacht*
flame	*roam*	*yelp*	*deaf*	*peon*	*yearn*
flare	*rogue*	*yoke*	*dearth*	*quay*	*yield*
flea	*scan*	*zinc*	*deuce*	*quiche*	*yolk*
flirt	*scout*		*doth*	*raft*	
force	*shack*		*dough*	*rasp*	
foul	*shelf*		*earl*	*realm*	
found	*shout*		*feud*	*ruse*	
frail	*shrug*		*fiend*	*scythe*	
freak	*slate*		*fold*	*seize*	
frown	*slob*		*folk*	*sewer*	
gauze	*slope*		*gasp*	*sewn*	
germ	*slug*		*gauge*	*shaft*	
glee	*smirk*		*geese*	*shield*	
glib	*snag*		*ghoul*	*shoe*	
gown	*spark*		*gist*	*shove*	
grail	*spray*		*halve*	*sown*	
graph	*spur*		*haste*	*suave*	
graze	*steal*		*hearse*	*suede*	
grove	*sting*		*heir*	*suite*	
harp	*stout*		*hind*	*sword*	