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Differential effects of stimulus context in sensory processing: Effets différentiels du contexte de présentation des stimuli sur les processus perceptifs

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Original article

Differential effects of stimulus context in sensory processing

Effets différentiels du contexte de présentation des stimuli sur les processus perceptifs

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Abstract

Stimulus contexts in which different intensity levels are presented to two sensory–perceptual channels can produce differential effects on perception: Perceived magnitudes are depressed in whichever channel received the stronger stimuli. Context differentially can affect loudness at different sound frequencies or perceived length of lines in different spatial orientations. Reported in hearing, vision, haptic touch, taste, and olfaction, differential context effects (DCEs) are a general property of perceptual processing. Characterizing their functional properties and determining their underlying mechanisms are essential both to fully understanding sensory and perceptual processes and to properly interpreting sensory measurements obtained in applied as well as basic research settings.

Résumé

Les contextes dans lesquels on présente des niveaux différents d'intensité de stimuli à deux canaux sensoriels/perceptuels, peuvent produire des effets différentiels sur la perception : les intensités perçues sont diminuées dans le canal recevant les stimuli les plus intenses. Le contexte peut affecter différentiellement la sonie de sons présentés à différentes fréquences ou la longueur perçue de lignes présentées dans différentes orientations spatiales. Démontrés en audition, vision, perception haptique, goût et olfaction, les effets différentiels de contexte sont une propriété générale du traitement perceptif. Caractériser ses propriétés fonctionnelles et déterminer ses mécanismes fondamentaux est essentiel pour comprendre les processus sensoriels et perceptifs, ainsi que pour interpréter correctement les mesures sensorielles réalisées dans le domaine de la recherche fondamentale comme appliquée.

Keywords: Contextual effects; Stimulus intensity; Perceptual magnitude; Sensory processes

Mots clés : Effets de contexte ; Intensité du stimulus ; Grandeur perceptive ; Processus sensoriels

1. Introduction

It has long been known that judgments of sensory magnitudes depend not only on the physical characteristics of each stimulus that is judged—on its intensity, duration, qualitative make-up, and so forth—but also on the physical characteristics and perceptual properties of other stimuli presented either recently or at the same time. Especially well-known in this regard is Helson's (1964) adaptation-level theory, developed in large measure to account for the ways that the judgments given to a test stimulus depend on the contextual ensemble of other stimuli that form its immediate background. A sound of fixed intensity and frequency, for example, may be rated as louder or softer in the context of other relatively weaker or stronger sounds—an example of sensory contrast.

Abbreviations: DCE, differential context effect; Hz, Hertz; RT, response time; SPL, sound pressure level.

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A line of investigation that began in the first author's laboratory nearly 20 years ago (Marks, 1988) led to the discovery of stimulus-specific context effects similar to, though far from identical to, those analyzed by Helson (1964) several decades earlier. These stimulus-specific or *differential contextual effects* are pervasive: They appear in virtually every sensory modality tested. Their functional characteristics suggest that they reflect sensory changes induced at an early stage in perceptual processing. Obviously, it is important, from a theoretical perspective, to understand these (and other) contextual effects if we are to understand fully the mechanisms of sensory information processing. Further, from a practical perspective, the omnipresence of differential contextual effects in perception and perceptual judgment also underscore their relevance to the proper interpretation of findings obtained in applied as well as basic research settings. Consequently, the present paper has three main goals: first, to review the main empirical findings on differential context effects (DCEs); second, to assess, given current understanding, the likely source or sources of the effects: whether they reflect relatively early sensory processes or later decisional ones; and third, to show how DCEs can affect experimental results obtained in studies assessing sensory or perceptual processes.

2. DCEs characterized

DCEs first appeared in a study that asked people to rate the perceived magnitude (loudness) of tones that varied multidimensionally, in their frequency as well as intensity (Marks, 1988). In the basic paradigm of that study, subjects were presented tones selected from an ensemble consisting of 12 possible intensity levels (sound pressure levels, or SPLs) at each of two sound frequencies, one low (500 Hertz, Hz) and another high (2500 Hz). In one contextual condition (A), subjects heard the eight lowest SPLs at 500 Hz and the eight highest SPLs at 2500 Hz, whereas in the second condition (B), the assignment of SPLs to frequency reversed, the subjects hearing the eight highest SPLs at 500 Hz and the eight lowest at 2500 Hz. Thus, four SPLs at each frequency were common to the two contextual conditions, and it is the responses to these common tones that are critical (Fig. 1).

A typical result is shown in Fig. 1, which plots the average numerical judgments (magnitude estimates) of loudness against SPL at 500 and 2500 Hz, separately in condition A (left side of figure) and condition B (right side of figure). Context clearly affected the relative (differential) responses at the two frequencies. Consider the responses to the 500 and 2500-Hz tones when both were presented at 60 dB SPL, as they were in both conditions. In condition A, the two tones were judged nearly equal in loudness, the 60-dB 2500-Hz tone receiving a very slightly greater judgment than the corresponding 500-Hz tone; but in condition B, the 2500-Hz tone was judged much louder than the 500-Hz tone. In general, considering just the four stimuli at each frequency common to the two contextual conditions, the 500-Hz tones were rated louder in condition A versus condition B, whereas the 2500-Hz tones were rated louder in condition B versus condition A. This is the prototypical pattern of DCEs.

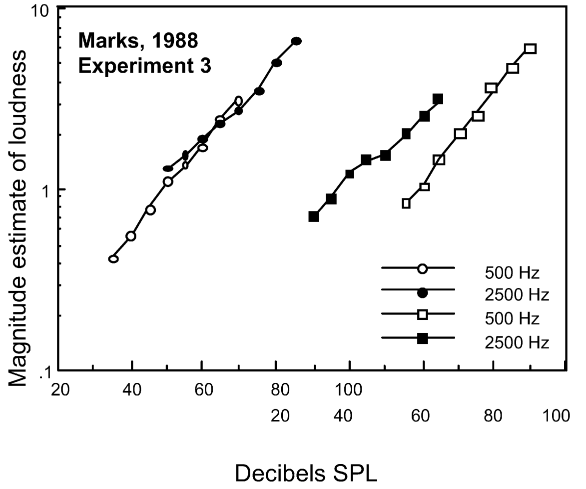

Fig. 1. Magnitude estimates of loudness of 500 and 2500-Hz tones. In contextual condition A (left), the SPLs at 500 Hz were low and those at 2500 Hz were high; in condition B (right), the SPLs at 500 Hz were high and those as 2500 Hz were low. Data from Marks (1988).

These contextual effects are not specific to the method of magnitude estimation. Similar contextual effects arise in tasks that use a variety of methods. For example, Schneider and Parker (1990) obtained similar findings when subjects compared loudness intervals. Importantly, DCEs appear even when the subject's task is simply one of direct comparison, that is, when the subject is presented on each trial with two stimuli in succession and simply indicates which of them is greater. Using ensembles of 500 and 2500-Hz tones constructed similarly to those in Fig. 1, direct loudness comparison also reveals DCEs (Marks, 1992a, 1994) (Fig. 2).

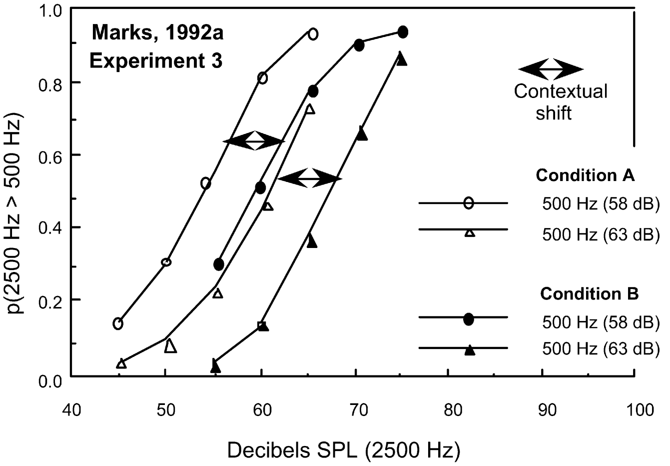

Fig. 2. Psychometric functions, showing how the probability that a 2500-Hz tone was judged louder than a 500-Hz tone, in two contextual conditions. In condition A (left-hand function in each successive pair, open symbols), the SPLs at 2500 Hz were 10 dB lower than they were in condition B (right-hand function in each successive pair, filled symbols), while the SPLs at 500 Hz were the same in both conditions. Changing the context displaces the functions as indicated, reflecting the changes in loudness. Data from Marks (1992a).

The study of Marks (1992a) provides an example. In this study, condition A paired each of three SPLs at 500 Hz with each of five SPLs at 2500 Hz, making 15 possible pairs of stimuli to be compared on a given trial; condition B paired the same three SPLs at 500 Hz with each of five SPLs at 2500 Hz, but the SPLs at 2500 Hz were 10 dB greater than those in condition A. As a result, the 2500-Hz tones were perceived to be relatively softer in condition B than A, as revealed by the displacement of the corresponding psychometric functions in Fig. 2. (For convenience of display, only two of the three pairs of functions are shown, but the third pair gave wholly analogous results.) To produce the same response proportions, the SPLs at 2500 Hz had to be 5–10 dB greater in condition B (filled symbols) compared to the corresponding SPLs in condition a (open symbols). Armstrong and Marks (1997) reported analogous findings in a paired comparison study of the visual perception of length of lines oriented vertically and horizontally: Changing the physical lengths of horizontal and vertical lines led to shifts in the psychometric functions analogous to the shifts shown in Fig. 2. Perceived length was reduced at whichever spatial orientation had the greater physical lengths.

What the data shown in Figs. 1 and 2 do not tell us is the nature of these contextual effects. Do these effects represent a reduction in loudness at a particular sound frequency when the average intensity level at that frequency is high, an enhancement in loudness when the average intensity level at the frequency is low, or both reduction and enhancement? Evidence reviewed later suggests that DCEs result from reductions in perceived intensity when stimulus levels are high, *sans* enhancement when levels are low. Unlike the upward and downward shifts from adaptation-level reported by Helson (1964), DCEs appear to consist exclusively of downward shifts in perceived magnitudes—although a small amount of enhancement is possible.

3. DCEs in hearing, vision, haptics, taste, and olfaction

3.1. When are DCEs present, and when are they absent?

The DCEs shown in Figs. 1 and 2 obviously depend on the presence of different sound frequencies. The role of sound frequency, or more precisely of the size of the difference in sound frequency (Δf in Hz), was tested in two subsequent studies (Marks, 1994; Marks and Warner, 1991). Both studies showed that the magnitude of the DCE depends systematically on the difference between the sound frequencies of the two tones (holding the geometric average of the sound frequencies constant). When Δf is small, DCEs are virtually absent. The DCE appears once Δf exceeds auditory 'critical bandwidth', the frequency difference that marks the shift in activation from a single region of activity on the basilar membrane to two minimally overlapping regions; with subsequent increase in Δf, the DCE increases in size toward an asymptotic level. This outcome suggests, although it does not by itself prove, that DCEs in loudness may be closely allied to relatively low-level auditory processes. In this regard, it is worth noting that 'low-level specificity' of DCEs extends also to vision. Arieh and Marks (2002) showed that the DCEs observed in the perception of length of horizontally and vertically oriented lines, discussed earlier, do not transfer substantially between the two eyes or to adjacent regions of the retina.

How widespread are DCEs? It is important to identify both where DCEs do occur and where they do not. To be sure, DCEs pervade the sensory realm: DCEs have been reported in five sensory modalities: hearing, vision, haptic touch (kinesthesis), taste, and olfaction. Thus, DCEs appear (a) in hearing, in judgments of loudness when the tones take on different frequencies (e.g. Marks, 1988; Schneider and Parker, 1990); (b) in vision, in judgments of length when lines take on different orientations (Armstrong and Marks, 1997; Arieh and Marks, 2002), in judgments of brightness when lights take on different colors (Marks, 1993b), and in judgments of contrast when gratings take on different spatial frequencies (Schneider et al., 1996); (c) in haptics (kinesthesis), in judgments of extent of arm movements made in different directions relative to the body (Marks and Armstrong, 1996); (d) in taste, in judgments of intensity of structurally different compounds such as sucrose and sodium chloride (Rankin and Marks, 1991, 1992); and (e) in olfaction, again in judgments of intensity of structurally different compounds, such as vanillin and orange (Rankin and Marks, 2000). Differential effects of stimulus context seem to characterize perceptual judgments in most of the senses, perhaps all of them.

On the other hand, DCEs are far from universal, and, from a theoretical perspective, the absence of DCEs can be just as important as their presence. To summarize, DCEs seem not to be found (or at least seem immeasurably small in size) when the two stimuli are processed through a single, common sensory channel. For example, DCEs are substantial in judgments of the loudness of 500 and 2500-Hz tones that vary contextually in SPL, as already discussed. But DCEs are absent from judgments of the duration of 500 and 2500-Hz tones that vary contextually in a similar fashion in their physical duration (Marks, 1992b). Whereas sound intensity is processed through what are largely separate channels for sound frequency (critical bands, different subsets of afferent fibers), auditory duration appears to be processed mainly through a single, frequency-independent channel. If the difference in sound frequency becomes sufficiently small (smaller than critical bandwidth), then all of the tones are processed through a single channel, and the DCE diminishes markedly or disappears (Marks, 1994; Marks and Warner, 1991).

Note that the absence of a *differential* effect of context does not necessarily mean that there is no contextual effect operating at all. If stimulus context affects perceptual responses to all of the stimuli equivalently, then the net *differential* effect will be nil, even though an absolute effect is present in the judgment of every stimulus. This is presumably what happens when, say, two sound frequencies take on different contextual sets of intensity levels, but the difference between the frequencies is smaller than critical bandwidth. In this case, the contextual effects pool more or less uniformly over all of the stimuli at the two frequencies. Consider the following design.

Although, to the best of our knowledge, it has never been used, it nevertheless serves as a useful *Gedanken* experiment: Subjects are presented, for loudness judgment or comparison, tones at three sound frequencies: 500, 2400, and 2600 Hz. In this case, tones at 500 Hz fall in one critical band, tones at 2400 and 2600 Hz in another. By appropriately manipulating the SPLs at these three frequencies, one should readily measure a DCE between the 500-Hz tones and the 2400-Hz tones and a DCE between the 500-Hz tones and the 2600-Hz tones; but one would not find a DCE between the 2400-Hz tones and the 2600-Hz tones—not because these tones were unaffected by the contextual manipulation, but because they were affected equally by it.

Similarly, DCEs are evident in vision when subjects judge the lengths of contextually varying horizontal and vertical lines, but are absent when subjects judge the length of contextually varying lines of different colors (Marks, 1992b). Whereas the perceived lengths of horizontal and vertical lines are presumably processed through different subsets of orientation-sensitive detectors in the visual cortex, the detectors operate independently of color. Again, this is not to say that lines presented in different colors are immune to effects of context, only that judgments will not show differential effects of context in terms of color. In principle, differential effects could be measured, however, by introducing a comparison stimulus having a different spatial orientation.

Lastly in this regard, substantial DCEs appear in taste perception, when subjects judge the perceived intensities of contextually varying sets of concentrations of sucrose and sodium chloride (Rankin and Marks, 1991) or of sucrose and quinine (Rankin and Marks, 1992). And again, the DCEs presumably arise because different gustatory receptors are maximally sensitive to sucrose, sodium chloride, and quinine. The DCEs are not evident, however, or at least are considerably smaller, when subjects judged contextually varying set of concentrations of sucrose and mixtures of sucrose with sodium chloride (Rankin and Marks, 1991) or contextually varying concentrations of sucrose and saccharin (Rankin and Marks, 1992). In each of these cases, the stimuli presumably activate largely overlapping populations of receptors. Once more, the absence of a DCE does not necessarily mean the absence of any contextual effect at all, but instead a more or less uniform pooling of the contextual effect over all of the stimuli in the ensemble.

3.2. Do DCEs rely on perceived dissimilarity or neural commonality?

The presence of DCEs in taste and olfaction (Rankin and Marks, 1991, 1992) provide a vehicle to answer a question raised but not answered in the studies of loudness: Do the DCEs reflect, and presumably reside in, the activation of different neural channels per se, as already argued, perhaps as the result of differential adaptation-like processes in these channels? Or do the DCEs arise from processes of perceptual comparison that ultimately depend on the perceived or psychological similarity/dissimilarity of the stimuli? That DCEs in loudness appear only when the sound frequencies differ by at least a critical bandwidth is consistent with the hypothesis that these effects reflect unequal adaptation (different degrees of intensity reduction) in different neural channels. But in hearing, when the difference between sound frequencies, Δf, increases, it is difficult to distinguish fully between a decrease in the overlap of channels and the correlated increase in perceived dissimilarity of pitch. As Δf increases, the populations of afferent fibers activated become more distinct, and the resulting pitch sensations become increasingly different. The existence of DCEs in taste and olfaction, however, provides a potential means to distinguish between the neural-channel hypothesis and the perceptual-dissimilarity hypothesis.

To compare the predictions of these two hypotheses, Rankin and Marks (2000) capitalized on two important properties of chemosensation. First, when olfactory stimuli are dissolved and taken into the mouth, they are typically perceived as though they are ‘tasted.’ In this process of retronasal olfaction, the odorant-based sensations are referred to the mouth—indeed, these olfactory-based sensations provide the lion’s share of what is commonly called ‘flavor’ in foods and beverages. Unlike gustatory sensations (e.g. the qualities of sweet, sour, salty, bitter, and umami (the ‘savory’ taste often used to describe the taste of monosodium glutamate), which derive from activation of receptors in the oral cavity, mainly on the tongue, retronasal olfactory sensations disappear if the nose is pinched. Rankin and Marks presented two gustatory stimuli, sucrose and citric acid, and two olfactory stimuli, vanillin and orange, in aqueous solutions through the mouth, allowing all of the stimuli to be ‘tasted’.

Second, Rankin and Marks (2000) chose vanillin and orange as olfactory stimuli not only because, at moderate concentrations, these stimuli have no taste proper (that is, produce no gustatory sensations) but also because vanillin in particular is perceived to be perceptually similar to sucrose. In a preliminary, similarity-scaling experiment, subjects judged the gustatory stimulus sucrose to be more similar to the olfactory stimulus vanillin (when both were taken into the mouth) than to the gustatory stimulus citric acid. Consequently, if DCEs depend on the activation of distinct neural channels, in this case, activation of different modalities, then DCEs should be present with stimulus ensembles comprising contextually varying concentrations of sucrose and vanillin. If, on the other hand, DCEs require that the sensations be perceptually dissimilar in quality, then DCEs should be absent (or at least small in size) in particular with varying contextual sets of sucrose and vanillin. The results were unequivocal: Sucrose and vanillin gave large DCEs, despite having similar perceptual qualities. In general, neural commonality in gustation and olfaction predicts the magnitude of DCEs better than does perceived dissimilarity. DCEs in taste and olfaction, at least, appear to require the activation of different afferent channels.

3.3. DCEs as reductions in sensory magnitudes

Because DCEs often occur when two different sets of stimuli are presented for comparison (e.g. tones differing in frequency, lines differing in spatial orientation), it may be tempting to infer that two different sets of stimuli must be presented in order to induce the effects. To the contrary, several experiments have now clearly shown that DCEs can arise from the presentation of just one kind of stimulus. Indeed, in the limiting case it appears that a DCE can result from a single presentation of a single stimulus.

Marks (1993a, Experiment 15) sought to dissociate the induction of DCEs in loudness from their measurement by having subjects first listen to context-inducing tones, then perform a series of paired comparisons to measure the perceptual consequence. This experiment compared the efficacy of six stimulus regimens in inducing the DCEs. In two of the regimens, the subjects listened to inducing tones that alternated between a low-SPL at one frequency (500 or 2500 Hz) and a high-SPL at the other (2500 or 500) Hz. In the other four regimens, the subjects listened to repeated presentations of just a single tone: 500 or 2500 Hz at the low or high-SPL.

Fig. 3 shows the results. All of the inducing regimens that included signals at high-SPL produced DCEs. That is, DCEs were evident with presentation of two inducing tones, one at high-SPL and the other at low-SPL, or with presentation of a single tone at high-SPL. By contrast, neither of the inducing regimens containing a single, low-SPL tone produced a DCE.

These findings make two important points: First, DCEs can arise simply from exposure to the context-inducing stimuli; the inducing tones need not themselves be judged. And second, the induction of DCEs requires the presentation of relatively high stimulus intensities, which presumably then come to suppress loudness. Mapes-Riordan and Yost (1999); Nieder et al. (2003) came to similar conclusions, using a paradigm in which, on each trial, subjects hear a single inducing tone followed by a test tone of the same frequency and then a comparison tone of a different frequency. If low stimulus intensities induce DCEs, the effects must be very small.

Experiments using other procedures (magnitude estimation, as in Fig. 1; paired comparison, as in Fig. 2; and paired comparison of differences, as in Schneider and Parker (1990) show comparable results: DCEs occur only when subjects listen to inducing tones of at least moderate intensity, at least 75–80 dB SPL in hearing. Brief presentations of weaker tones have no significant effect (Mapes-Riordan and Yost, 1999; Marks, 1993a; Nieder et al., 2003). A similar outcome was reported in the visual perception of length of lines: Presenting relatively long lines in vertical or horizontal orientation produces a DCE, whereas presenting relatively short lines does not (Armstrong and Marks, 1997). Thus considered, DCEs seem best characterized as evidencing stimulus-specific adaptation. Although sensory adaptation often requires more than transient exposure to stimuli, this is not always the case. Where dark adaptation (recovery from light adaptation) takes several minutes, brief flashes of light can produce significant light adaptation, lasting many seconds. And in the auditory realm, phonetic adaptation takes place in speech perception (e.g. Samuel, 1986; Sawush, 1977), and speech sounds such as phonemes are, ipso facto, transient stimuli.

4. Mechanisms underlying DCEs

As a working hypothesis, DCEs may be subsumed under the broad category of adaptation or adaptation-like phenomena. The contextual effects on loudness at different sound frequencies, for instance, have recently been called ‘induced loudness reduction’—a reasonable descriptive term, given that loudness adaptation has been defined exclusively as the changes in loudness of sounds over long periods of time; changes in sensitivity or response resulting from transient exposure to very intense sounds is labeled in psychoacoustics as ‘fatigue.’ Nevertheless, a central theoretical question asks whether DCEs represent channel-specific sensory changes—changes in the underlying neural and psychological representations of perceptual magnitudes—or changes in decisional criteria.

Consider the following example. Assume that at baseline, before any contextual manipulation, subjects judge 500-Hz tones and 2500-Hz tones that are equal in SPL to be equal in loudness. Thus, a 65-dB tone at 500 Hz is judged as loud as a 65-dB tone at 2500 Hz. After baseline measurement, subjects then listen to several repetitions of a 2500-Hz tone presented at

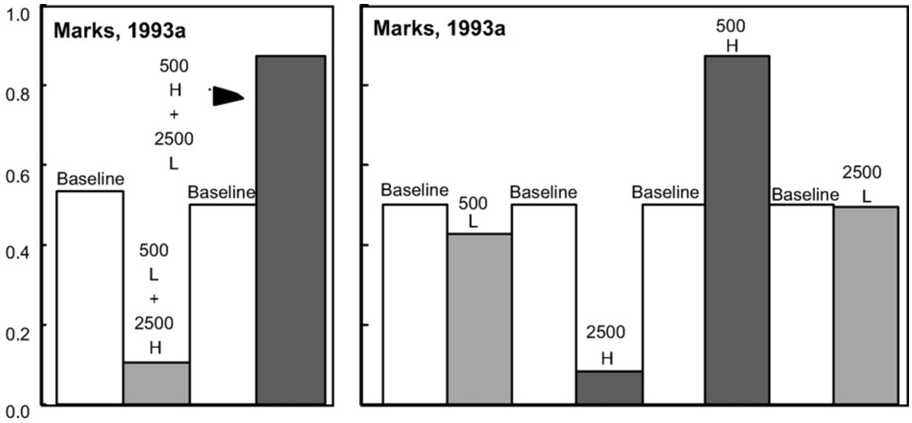

Fig. 3. The probability of judging a 2500-Hz tone louder than a 500-Hz tone before (baseline) and after listening to a sequence of inducing tones. Left panel: Sequences contained 40 low-SPL 500-Hz tones and 40 high-SPL 2500-Hz tones (condition A) or 40 high-SPL 500-Hz tones and 40 low-SPL 2500-Hz tones (condition B). Right: Sequences contained 40 low-SPL 500-Hz tones, 40 high-SPL 2500-Hz tones, 40 low-SPL 500-Hz tones, or 40 high-SPL 2500-Hz tones. Data from Marks (1993a).

either 30 dB or 80 dB SPL. Presenting the 30-dB tone leaves loudness unaffected: a 65-dB tone at 2500 Hz is still as loud as a 65-dB tone at 500 Hz. But presenting the 80-dB tone reduces loudness at 2500 Hz. Now, in order to match the loudness of a 2500-Hz tone at 65 dB, the SPL of a 500-Hz tone needs be only 58 dB. Context has reduced the loudness, or the loudness judgment, at 2500 Hz by the equivalent of 7 dB. Now, two explanations are possible, encapsulated by the terms 'loudness' and 'loudness judgment' in the last sentence. Context may have reduced the underlying sensory response (loudness) by 7 dB. Alternatively, context may have influenced the process of loudness comparison, so that subjects now 'judge' loudness at 2500 Hz to be smaller even though the sensory representation is unchanged.

Is it possible to distinguish sensory from decisional explanations of DCEs? Methods and theory of signal detection theory provide a possible means—if, for example, DCEs were evident at threshold, where detection paradigms could be used. Unfortunately, DCEs are absent at threshold (Mapes-Riordan and Yost, 1999). Fortunately, it is possible to transfer the decision-theoretic logic of signal detection theory to the realm of speeded choice response paradigms, where the joint analysis of response times (RTs) and errors can play a role akin to that of receiver operating characteristics in signal detection theory. In brief, when subjects are faced with a task requiring different responses to stimulus A and stimulus B, and these responses are to be made as quickly as possible, then speed and accuracy often trade: As the subjects respond more rapidly, the gain in speed (reduction in time) is offset by an increase in errors—analogous to the increase in false alarms that occurs when hit rate increases in tasks of signal detection and discrimination.

Using this logic, Arieh and Marks (2003a) transposed the original loudness-rating paradigm of Marks (1988) into a speeded choice paradigm. In doing this, Arieh and Marks relied on the well-established finding that RT can serve as a surrogate for perceived magnitude: When stimulus intensity increases, sensory magnitude also increases, while RT to the stimulus decreases, though sometimes approaching a lower asymptote at high intensities. Further, RT can serve as a surrogate for perceived intensity both in simple RT paradigms, where subjects respond to the onset of any stimulus as quickly as possible, and in choice RT paradigms, where subjects must identify the stimulus by making one response or another.

In their choice experiment, Arieh and Marks (2003a) asked subjects to decide as quickly as they could whether the frequency of each test tone was low (500 Hz) or high (2500 Hz), while in different conditions the contextual set of intensity levels varied. Arieh and Marks asked the following questions: When the SPLs at 2500 Hz increase, thereby decreasing loudness at 2500 Hz, does RT at 2500 Hz increase correspondingly? And if RT does increase, is the increase in RT accompanied by a corresponding decrease in errors (speed-accuracy tradeoff, indicating decisional change) or by no change in errors (no speed-accuracy tradeoff, indicating a sensory change)?

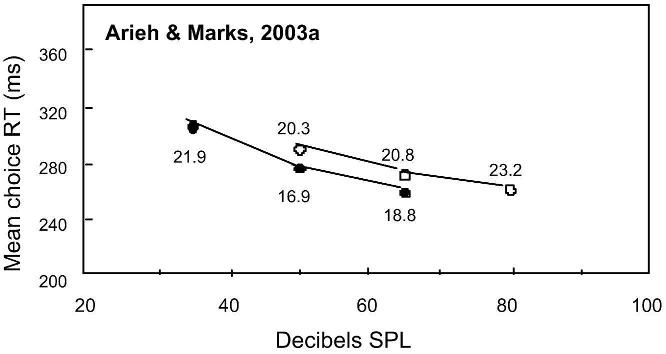

Fig. 4. Choice RTs (y axis) and error rates (listed next to each data point) for 500-Hz tones in two contextual conditions. In condition A (filled circles) the SPLs at 500 Hz were low and those at 2500 Hz (not shown) were high; in condition B (open circles) the SPLs at 500 Hz were high and those at 2500 Hz (not shown) were low (data from Arieh and Marks, 2003a).

Fig. 4 shows a sample of the results. The 500-Hz tones at 50 and 65 dB were classified faster in condition A, where the average SPL was relatively low, than condition B, where the average was higher. Importantly, subjects also made fewer errors in condition A, whereas the decisional model predicts more errors. These results are clear-cut: RTs show DCEs as expected, and the changes in choice RT are not accompanied by offsetting changes in accuracy. The findings are therefore consistent with the hypothesis that the DCEs reflect changes in the underlying sensory representations of loudness.

Recent research, in several different laboratories, has sought to evaluate contextually induced changes in loudness in greater detail, and in particular to evaluate the temporal properties of these DCEs—which some investigators have dubbed 'induced loudness reduction' (see Scharf et al., 2002; Nieder et al., 2003). In one of it simplest instantiations, the subjects hear a single context-inducing stimulus, whose effects are tested at various points in time afterwards. Arieh and Marks (2003b) found no decrease in loudness for the first 150 ms after the offset of the inducing stimulus. The maximal effect occurred about 825 ms after the inducer's offset. Moreover, according to recent evidence, full recovery after exposure to as few as five inducing stimuli can take scores of seconds, even minutes (Arieh et al., 2005). That DCEs dissipate slowly has important consequences for sensory measurement.

5. DCEs and sensory evaluation

In this final section, we describe two of the many ways that DCEs may 'intrude' on sensory evaluations. In each case, the DCE results from a mismatch between two sets of stimuli—or, and this is more likely to be critical, from a mismatch between the perceptual magnitudes produced by the two sets of stimuli. These examples are meant to serve only as illustrations of the ways that contextual effects pervade research on basic and applied topics in sensation and perception. It is important to keep in mind three central characteristics of DCEs: First, they are ubiquitous, appearing in virtually all if not all sensory modalities. Second, they are relatively long lasting, a few brief stimuli being capable of effecting changes that last more than a minute. And third, they arise automatically, in a wide variety of psychophysical paradigms. Almost any stimulus ensemble that includes moderately high levels, such as tones of about 80 dB or greater, is capable of producing an adaptation-like effect. Whether the effects matter to the scientific questions being asked, however, often depend on whether there is an opportunity for the presence of *differential* effects. If the contextual effects apply equally to all stimuli in the ensemble, then the effects are not differential. Many experimental paradigms, however, do permit the opportunity for differential effects to arise, as shown in the following pair of examples.

5.1. Differential effects of stimulus context on perceptual illusions

The first example arises from the observations of DCEs in the judgment of linear extent, when made both by vision and by haptic touch. In vision, the perceived length of horizontal and vertical lines depends systematically on contextual sets of physical lengths presented in the two spatial orientations (Armstrong and Marks, 1997; Arieh and Marks, 2002; Potts, 1991). Presenting physically long vertical lines reduces the perceived length of verticals, and presenting physically long horizontal lines reduces the perceived length of verticals. Thus, the ratio of perceived vertical length to perceived horizontal length is sensitive to stimulus context.

The presence of DCEs in judgments of visual length bears consequences in turn for the well-known horizontal–vertical illusion in vision: the tendency for vertical lines to appear greater than horizontal lines of the same physical length. Although the illusion is often studied with configural stimuli—the horizontal and vertical segments being joined either at the ends, in an L configuration, or at the center of the horizontal, in a T configuration—the illusion is also readily shown in isolated line segments (Armstrong and Marks, 1997; Potts, 1991; Prinzmetal and Gettleman, 1993). In relatively ‘neutral’ conditions, the illusion amounts to about 8%—which means that the horizontal segment needs to be about 1.08 times as long, physically, as the vertical to be judged equally long. If visual length is proportional to physical length, then it also means that a vertical will appear about 8% longer than a physically equal horizontal. But, as we said, the 8% rule holds only in neutral conditions, where there are no DCEs. Increasing the lengths of the set of verticals reduces the perceived length of verticals, thereby reducing the size of the horizontal–vertical illusion, while increasing the length of the set of horizontals reduces the perceived length of horizontals, thereby increasing the size of the illusion (Armstrong and Marks, 1997; Potts, 1991).

Haptic touch is susceptible to an analogous illusion, known as the radial-tangential illusion, or RTI. Movements of the arm radial to the torso (e.g. away from the front of the body) are perceived as greater than physically equal movements made tangential to the torso (e.g. across the frontal plane) (Wong, 1977). But because perceived extent of arm movements is susceptible to differential effects of stimulus context based on direction of movement, the magnitude of the RTI itself is contextually sensitive (Marks and Armstrong, 1996). Both the horizontal–vertical illusion in vision and the RTI in haptics (kinesthesis) depend systematically on stimulus context.

5.2. Effects of aging in chemosensation

A topic that has commanded great attention in recent years is the effect of aging on sensory and perceptual processing. Of special interest here are studies showing age-related changes in chemosensory function. Several lines of inquiry have shown, for example, marked age-related losses of olfactory function, as assessed by the ability to identify odorants (e.g. Doty et al., 1984; Larsson et al., 2000) and to detect them (e.g. Cain and Gent, 1991). A few studies have also sought to quantify the degree to which perceived olfactory intensity declines with age, a topic that is particularly relevant to eating and food intake: Most of a food’s flavor (‘taste’, in the vernacular) comes from olfaction—from the activation of olfactory receptors by air-borne molecules that travel from the mouth to olfactory mucosa retronasally, through the nasopharynx. Because olfactory magnitudes decline with age (Stevens and Cain, 1985), these declines could account for the common complaint made by many elderly individuals that foods have ‘lost their taste’.

To assess how age can affect perceived odor intensities, some investigators have used procedures in which young and older subjects rate, on a common sensory scale, the intensities of stimuli presented in two modalities: olfaction, the modality of interest, and a second, calibrating, modality, chosen to be relatively impervious to effects of age (e.g. Stevens and Cain, 1985). By comparing the responses given to olfactory stimuli to responses given to stimuli on the calibrating modality, it should be possible, in principle, to assess the relative change in olfaction due to age. The question we ask here is, could DCEs influence the outcome?

At first glance, it might appear that DCEs should not affect the outcome of interest—the difference between relative olfactory responses in young and old—because, in the experiments just described, the young and old subjects are presented identical sets of stimuli, both to olfaction and to the calibrating modality. And, to be sure, if DCEs depend on stimulus intensity per se, then the DCEs should be equivalent in the two age groups. Differential effects may be present, but if so, then they should be equal in the young and old, and therefore should not modify the effect of age. But further consideration suggests a more complicated picture.

Let us assume that older subjects do perceive odor intensities to be weaker than younger subjects do. Then, by presenting the same stimuli to both groups, the older subjects will experience weaker olfactory sensations than will the younger ones. We have already noted that DCEs are induced only by strong stimuli; further, it is reasonable to assume that this normally happens because strong stimuli also produce strong sensory responses. If so, then the strength of the olfactory sensations evoked in the older subjects will resemble the strength of sensations evoked by lower concentrations in younger subjects. To the young subjects, the odorants delivered in the experiment are perceived as relatively strong, and thus the perceived magnitudes are contextually reduced (relative to the calibrating modality). To the old subjects, however, the odorants are less strong, and so their perceived magnitudes are not reduced contextually, or are reduced less than they are in the young. If the olfactory sensations are contextually reduced to a greater extent in the younger than the older subjects, then the results will show a smaller effect of age than they would were the contextual effects in young and old equal. In brief, by presenting the same stimuli to both young and older subjects, the effect of aging could be underestimated.

Marks et al. (1988, Experiment 9) tested the implications of this line of reasoning by having young (20–35-year-old) and older (65–79-year-old) subjects rate, on a common magnitude-estimation scale, the odor intensity of butyl alcohol (butanol) and the taste intensity of sodium chloride (the latter is not noticeably affected by age). In the first condition of the experiment, the two groups received the same sets of olfactory and gustatory stimuli, and the results showed a substantial effect of aging: The olfactory stimuli were judged 25% weaker by the old versus the younger subjects, when calibrated against the judgments of sodium chloride. If, however, there were effects of stimulus context, as just argued, then the olfactory judgments were reduced by DCEs to a greater extent in the young than the older subjects, and the results obtained in the first condition thereby underestimate the effect of age.

Given these considerations, Marks et al. (1988) ran a second condition with the same subjects: The young subjects received exactly the same concentrations of butanol and sodium chloride that they received in the first condition, but the older subjects received higher concentrations of butanol only, selected to compensate for their loss in olfactory response, and thereby to equalize the DCEs in the two groups. After adjusting stimulus concentrations in this manner, the results obtained in the second condition showed an even greater effect of age on olfactory responses: Now the olfactory stimuli were depressed by more than 50% in elderly compared to young subjects. By implication, in the first condition, the DCEs had reduced the magnitude of the age effect by more than half.

6. Conclusion

It is a truism to say that contextual effects pervade human sensory processing and perceptual judgments. But truisms are, by definition, true, and often they are useful. Contextual effects pervade perception and perceptual judgments, both in laboratory settings and in the world outside the laboratory. When the recent context includes brief, moderately strong stimuli that are processed through different neural channels (e.g. critical bands of sound frequency in hearing, horizontal and vertical spatial orientations in vision), the stimuli can produce subsequent decrements in perceived magnitudes. And if these decrements in magnitude are unequal in different processing channels, the result is a DCE: Stimuli processed through the channel that received the strongest contextual stimuli are perceived as relatively weaker than stimuli processed through other channels.

Differential effects of stimulus context have been reported in hearing, vision, haptic touch (kinesthesis), taste, and olfaction and thus probably reflect a general characteristic of intensity processing in the nervous system—most likely, low-level “adaptation-like” processes rather than high-level decisional biases. Stimulus contexts have been shown, for example, to affect perceptual illusions, such as the horizontal–vertical illusion in vision and the RTI in kinesthesis, and measurements of the effect of aging on olfactory perception. Differential effects of stimulus context are ubiquitous, and it can be perilous to ignore them.

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