

on routine monitoring of workers exposed to low levels of benzene.

The present study showed that total WBCs, granulocytes, lymphocytes, B cells, and platelets significantly declined with increasing benzene exposure and were lower in workers exposed to benzene at air levels of 1 ppm or less compared to controls. Our findings are particularly robust because we carried out extensive exposure assessment over a 16-month period (8) and linked individual air-monitoring data to the end-points measured. Further, we showed that benzene exposure decreased colony formation from myeloid progenitor cells, and that these progenitors were more sensitive to benzene toxicity than were mature WBCs. Finally, genetic variation in *MPO* and *NQO1* conferred susceptibility to benzene-induced lowering of WBC counts. Although confirmation of these findings in other studies is needed, these data provide evidence that benzene causes hematologic effects at or

below 1 ppm, particularly among susceptible subpopulations.

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#### Supporting Online Material

[www.sciencemag.org/cgi/content/full/306/5702/1774/DC1](http://www.sciencemag.org/cgi/content/full/306/5702/1774/DC1)

Materials and Methods

SOM Text

Fig. S1

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References

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## A Survey Method for Characterizing Daily Life Experience: The Day Reconstruction Method

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The Day Reconstruction Method (DRM) assesses how people spend their time and how they experience the various activities and settings of their lives, combining features of time-budget measurement and experience sampling. Participants systematically reconstruct their activities and experiences of the preceding day with procedures designed to reduce recall biases. The DRM's utility is shown by documenting close correspondences between the DRM reports of 909 employed women and established results from experience sampling. An analysis of the hedonic treadmill shows the DRM's potential for well-being research.

How do people experience the settings and activities of their lives? How do they use their time? These questions are usefully considered together, but there is no generally accepted method for collecting the relevant data. Quantitative information about time use and the frequency and intensity of stress, enjoyment, and other affective states is

potentially useful to medical researchers for assessing the burden of different illnesses (1) and the health consequences of stress (2); to epidemiologists interested in social and environmental stressors (3); to economists and policy researchers for evaluating policies and for valuing nonmarket activities (4, 5); and to anyone who wishes to measure the well-being of society. In particular, economic models that define well-being by the temporal integral of momentary experienced utility (6–8) require detailed measures of the quality and duration of people's experiences in daily life.

Information about the allocation of time in the daily life of the population is a component of national statistics in several countries. With rare exceptions (4, 9), time-budget studies have not included measures of

the satisfaction people derive from their activities. Similarly, questions about time-use and about the subjective experience of specific situations are rarely included in surveys of subjective well-being. Instead, these studies usually rely on global reports of happiness or satisfaction with life in general, or with domains such as work and family (10, 11).

The development of the experience sampling method (ESM) (12) and of ecological momentary assessment, which encompasses all momentary phenomena including physiological events (13), marked a notable advance in the measurement of the quality of people's lives. Participants in ESM studies are prompted to record where they are, what they are doing, and how they feel several times throughout the day. This technique provides a rich description of a sample of moments in respondents' lives, while avoiding the distortions that affect the delayed recall and evaluation of experiences (14). However, experience sampling is expensive, involves high levels of participant burden, and provides little information about uncommon or brief events, which are rarely sampled.

We present a new hybrid approach, the DRM, which combines a time-use study with a technique for recovering affective experiences. DRM respondents first revive memories of the previous day by constructing a diary consisting of a sequence of episodes. Then they describe each episode by answering questions about the situation and about the feelings that they experienced, as in experience sampling. The goal is to provide an accurate picture of the experience associated with activities (e.g., commuting) and circumstances (e.g., a job with time press-

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sure). Evoking the context of the previous day is intended to elicit specific and recent memories, thereby reducing errors and biases of recall (14, 15). Experience sampling is the gold standard to which DRM results must be compared; the DRM is intended to reproduce the information that would be collected by probing experiences in real time. The new method is more efficient than ESM: It imposes less respondent burden; does not disrupt normal activities; and provides an assessment of contiguous episodes over a full day, rather than a sampling of moments. Finally, the DRM provides time-budget information, which is not collected effectively in experience sampling.

We demonstrate the method with a convenience sample of 1018 employed women, focusing on the subset of 909 who had worked on the reference day. The questionnaire and methodological details are available online (16). Completion times for the self-administered instrument ranged from 45 to 75 min. The ethnic composition of the sample was 49% white (non-Hispanic), 24% African American, 22% Hispanic, and 5% other. Average age was 38 years. Average household income was \$54,700.

Respondents first answered demographic and general satisfaction questions. Next, they

were asked to construct a short diary of the previous day: "Think of your day as a continuous series of scenes or episodes in a film. Give each episode a brief name that will help you remember it (for example, 'commuting to work', or 'at lunch with B'...). Write down the approximate times at which each episode began and ended. The episodes people identify usually last between 15 minutes and 2 hours. Indications of the end of an episode might be going to a different location, ending one activity and starting another, or a change in the people you are interacting with." Respondents were not required to turn in their diary. The average number of episodes was 14.1 (SD = 4.8), and average episode duration was 61 min. Next, respondents answered structured questions about each episode: When it occurred (start and end times); what they were doing (by checking one or more of 16 activities); where they were; with whom they were interacting; and how they felt, using 12 affect descriptors, listed in Table 1. The affect scales ranged from 0 (not at all) to 6 (very much). Finally, respondents answered questions about their jobs and other personal details.

To show the results of the DRM, Table 1 presents affect ratings of situations, grouped

by activity (e.g., eating or working) or by interaction partner. The values shown are average ratings of particular experiences. They differ in interesting and predictable ways from generic enjoyment ratings of the same activities. Juster (4) and Flood (9), for example, observed that interactions with one's children topped the list of enjoyable activities, followed by going on trips, being with friends, and working at one's job. Grocery shopping and cleaning the house were rated lowest among 28 activities. In Table 1, taking care of one's children ranks just above the least enjoyable activities of working, housework, and commuting. The contrasting results likely reflect the difference between belief-based generic judgments ("I enjoy my kids") and specific episodic reports ("but they were a pain last night"). The task of judging a category of events evokes instances that are prototypical but not necessarily typical, and discourages reports of socially inappropriate affect (14). These deficiencies are attenuated when respondents describe specific episodes, as they do in the DRM.

Table 1 shows a large difference between positive and negative affect. Negative affect is relatively infrequent and mild, and the total absence of positive affect is rare. In

**Table 1.** Mean affect by situation. Positive affect is the average of happy, warm/friendly, enjoying myself. Negative affect is the average of frustrated/annoyed, depressed/blue, hassled/pushed around, angry/hostile, worried/anxious, criticized/put down. For each situation, the table shows the mean ratings on

affect descriptors, the average amount of time all respondents spent in the situation, and the proportion of respondents reporting at least one episode of that type. Episodes for which the respondent reported multiple activities or interaction partners were included in each of the corresponding computations.

	Mean affect rating					Mean hours/ day	Proportion of sample reporting
	Positive	Negative	Competent	Impatient	Tired		
Activities							
Intimate relations	5.10	0.36	4.57	0.74	3.09	0.2	0.11
Socializing	4.59	0.57	4.32	1.20	2.33	2.3	0.65
Relaxing	4.42	0.51	4.05	0.84	3.44	2.2	0.77
Pray/worship/meditate	4.35	0.59	4.45	1.04	2.95	0.4	0.23
Eating	4.34	0.59	4.12	0.95	2.55	2.2	0.94
Exercising	4.31	0.50	4.26	1.58	2.42	0.2	0.16
Watching TV	4.19	0.58	3.95	1.02	3.54	2.2	0.75
Shopping	3.95	0.74	4.26	2.08	2.66	0.4	0.30
Preparing food	3.93	0.69	4.20	1.54	3.11	1.1	0.62
On the phone	3.92	0.85	4.35	1.92	2.92	2.5	0.61
Napping	3.87	0.60	3.26	0.91	4.30	0.9	0.43
Taking care of my children	3.86	0.91	4.19	1.95	3.56	1.1	0.36
Computer/e-mail/Internet	3.81	0.80	4.57	1.93	2.62	1.9	0.47
Housework	3.73	0.77	4.23	2.11	3.40	1.1	0.49
Working	3.62	0.97	4.45	2.70	2.42	6.9	1.00
Commuting	3.45	0.89	4.09	2.60	2.75	1.6	0.87
Interaction partners							
Friends	4.36	0.67	4.37	1.61	2.59	2.6	0.65
Relatives	4.17	0.80	4.17	1.70	3.06	1.0	0.38
Spouse/SO	4.11	0.79	4.10	1.53	3.46	2.7	0.62
Children	4.04	0.75	4.13	1.65	3.40	2.3	0.53
Clients/customers	3.79	0.95	4.65	2.59	2.33	4.5	0.74
Co-workers	3.76	0.92	4.43	2.44	2.35	5.7	0.93
Boss	3.52	1.09	4.48	2.82	2.44	2.4	0.52
Alone	3.41	0.69	3.76	1.73	3.12	3.4	0.90
Duration-weighted mean	3.89	0.84	4.31	2.09	2.90		
% time > 0	97%	66%	90%	59%	76%		

both respects, the DRM replicates results obtained with experience sampling (12, 13).

We also compared the diurnal rhythm of tiredness and affect to the corresponding patterns exhibited in experience sampling data (17) (Fig. 1). Despite demographic differences between the samples, the diurnal cycles of affect and tiredness produced by both methods are remarkably similar. This is especially impressive for tiredness because the V-shaped diurnal pattern differs from the naïve expectation that tiredness increases steadily throughout the day. Negative affect was most pronounced in the morning and then fell for most of the day. These results suggest that participants were generally successful in recovering their actual experience. The diurnal pattern of tiredness is also similar to the diurnal pattern of on-the-job work accidents (18).

Figure 2A displays the diurnal pattern of tiredness for participants who reported that they slept a nightly average of 6 hours or less, or 7 hours or more, in the last month. Each group exhibits the V-shape pattern and, quite plausibly, those who slept less are more tired at each hour of the day. Figure 2B shows the diurnal pattern of tiredness for three age groups. The V-shape pattern is particularly pronounced for the young (under 30), who start off their day much more tired than their older counterparts, but then converge to roughly the same level of tiredness

by midday. It is extremely unlikely that DRM participants produced these patterns by consulting general beliefs about how tired or cheerful they are at various times of the day. Furthermore, the plausibility of the results suggests that respondents used the scales in a similar way, lending credence to interpersonal comparisons of reported affective experience.

In well-being research, the standard deviation of individual differences is normally the metric used to express the size of group differences. Because the DRM supports both between-subjects comparisons (e.g., different age groups) and within-subject comparisons (e.g., different situations or times of day), it provides an additional metric that facilitates the interpretation of results. Exploiting the broad consensus that exists on the relative enjoyment value of many activities and situations, we constructed a scale of enjoyment demarcated by types of familiar situations. We first chose two activities near the extremes of low and high enjoyment: commuting to work (mean = 2.86) and relaxing with friends

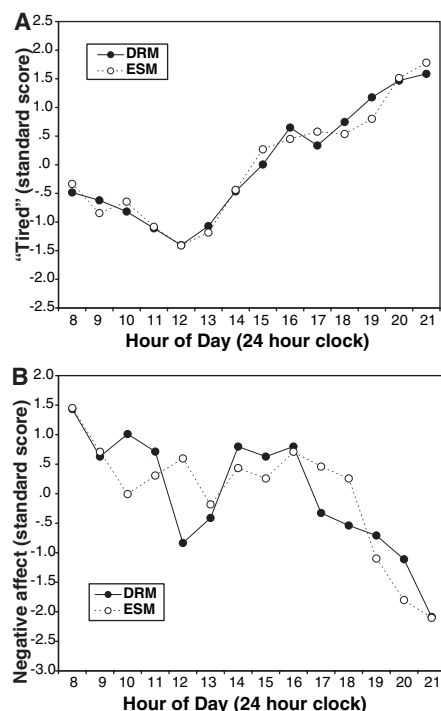
(mean = 4.92). We then identified five other activities with mean enjoyment ratings spaced approximately evenly within that range. The selected activities satisfied two conditions: (i) There was no significant difference in the overall average of enjoyment ratings between individuals who engaged in the activity and others who did not; and (ii) there was broad agreement between the rankings of the activities in the DRM results and in generic judgments of their enjoyment value (19, 20). Using this scale, we display the effects of selected work circumstances and individual differences on reported enjoyment, at work and at home (Fig. 3).

Line A shows the enjoyment of work episodes reported by respondents who do ( $n = 200$ ; mean = 2.88) or do not ( $n = 179$ ; mean = 3.96) report time pressure at work. The difference is about as large as the difference in enjoyment between “commuting to work” (mean = 2.86) and “shopping with your spouse/significant other” (SO) (mean = 3.90). Time pressure at work is unrelated to enjoyment in home situations (line B). Controlling for other job features (21) does not change these results, suggesting that time pressure is a particularly important determinant of enjoyment at work (22). Whereas the effect of time pressure is 52% as large as the enjoyment difference between commuting to work and relaxing with friends, being “at risk of being laid off” (line C) or having a job that requires “specialized education or training” (line D) exhibited a much smaller effect.

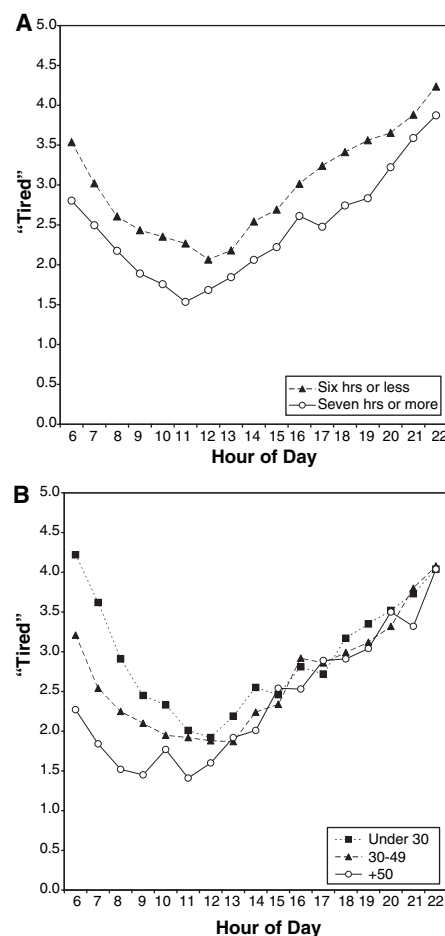
A similar analysis can be applied to personal characteristics. For example, differences in reported sleep quality are associated with a very large difference in reported enjoyment during episodes at home (line E). The effect is 56% of the entire scale range. Controlling for other personal features slightly reduces this effect (23). Differences in temperament and personality have similarly large effects (24), whereas the influence of other individual characteristics is much smaller. Substantial differences in household income have a modest influence on enjoyment (line G, 19%), which shrinks to marginal statistical significance under controls. The effect of religion is similar (line F, 19%), but shrinks less after controls, and the difference in enjoyment between divorced and married women (which slightly favors the divorced) is still smaller (line H).

We conclude that positive affect and enjoyment are strongly influenced by aspects of temperament and character (e.g., depression and sleep quality) and by features of the current situation. In contrast, general circumstances (e.g., income and education) have little impact on the enjoyment of a regular day.

These findings parallel the observation that life circumstances have surprisingly



**Fig. 1.** Comparison of diurnal patterns of tiredness (A) and negative affect (B) for DRM and ESM studies. Points are standard scores computed across hourly averages within each sample.



**Fig. 2.** Comparison of diurnal patterns of tiredness by average hours of sleep per night (A) and by age (B) for the DRM sample. Points are hourly averages within each subsample.

little influence on global reports of life satisfaction. For example, large increases of real income in the developed world over the past 50 years have yielded no change in reported life satisfaction (25). The observation that improved life circumstances quickly cease to provide increased satisfaction has been called the hedonic treadmill (26). Our data allow us to compare the impact of life circumstances on affective experience and on global life satisfaction (27). We considered three hypotheses. The hedonic treadmill hypothesis holds that life satisfaction and affective experience are equally susceptible to adaptation. The aspiration treadmill hypothesis holds that treadmill effects observed in satisfaction judgments are due mainly to changing standards (28). Thus, the rich may experience more pleasure than the poor, but they also require more pleasure to be equally satisfied. Accordingly, real differences in enjoyment are not reflected in satisfaction. Finally, the focusing hypothesis predicts that the effects of life circumstances on reported satisfaction, though small, actually overstate the effects on experience (29). The task of evaluating one's life, in part, evokes a comparison of one's objective circumstances to conventional standards, reminding the rich that they are rich and the divorced that they are divorced. Because these circumstances are most likely to come to the mind of the newly rich or recently divorced, their influence on satisfaction judgments declines over time, producing adaptation. The relative impact of life circumstances on actual affective experience is even smaller, because thoughts of one's circumstances are much more likely to come to mind when answering questions about one's life than in the routine course of experience. Affective experience as assessed by the DRM is less dependent on comparison standards than is evaluative judgment as assessed by global satisfaction questions.

To our surprise, the test favored the focusing hypothesis over the alternatives. Life satisfaction is moderately correlated ( $r = 0.38$ ) with daily "net affect" (the difference between positive and negative affect). The correlations of objective circumstances with life satisfaction are low, replicating the original treadmill puzzle, but their impact on affective experience is even smaller. For example,  $\log(\text{household income})$  correlates more with life satisfaction ( $r = 0.20$ ) than with net affect ( $r = 0.05$ ;  $P < 0.001$  for the difference). The corresponding values for the married/divorced distinction are 0.10 and  $-0.08$  ( $P < 0.001$ ), where married women report slightly higher satisfaction and divorced women report slightly more positive affect. In contrast, personal characteristics related to temperament and personality correlate at least as strongly with affect as with life satisfaction. Reported sleep quality ( $r =$

0.30 versus 0.28 for life satisfaction, nonsignificant) and an indicator of depression ("trouble maintaining enthusiasm";  $r = 0.44$  versus 0.28 for life satisfaction;  $P < 0.01$ ) are illustrative examples.

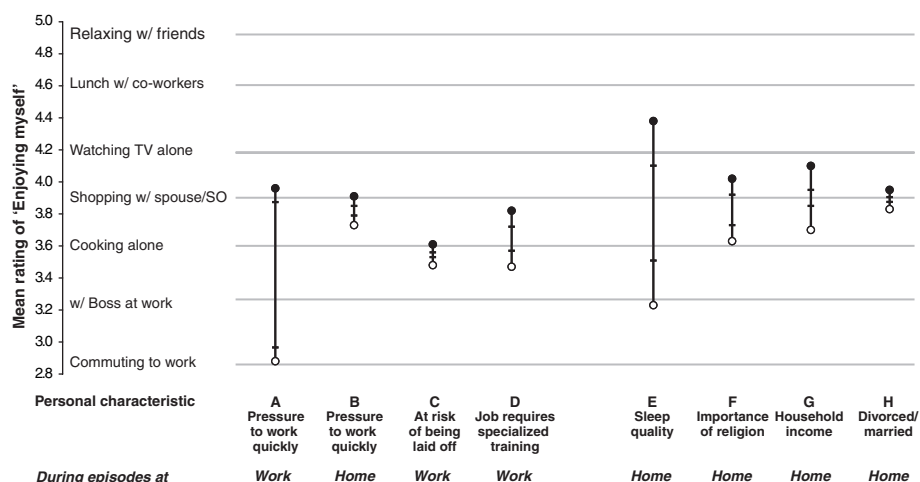
Similarly, long-term job circumstances tend to have more impact on job satisfaction than on the affective experience of the working day. For example, the report of "excellent benefits" correlates 0.18 with job satisfaction and 0.10 with affect at work (difference  $P < 0.05$ ). The corresponding correlations for "my job requires specialized training" are 0.20 and 0.09, respectively ( $P < 0.01$ ). The few job characteristics that influence affect more than job satisfaction are features of the immediate work situation, including time pressure ( $r = -0.28$  for job satisfaction versus  $-0.19$  for affect at work;  $P < 0.01$ ) and "opportunity to talk with coworkers" ( $r = 0.10$  for job satisfaction versus 0.02 for affect at work;  $P < 0.05$ ).

These findings suggest a possible resolution of the treadmill puzzle. Three distinct patterns can be identified in the affect results: (i) Personal characteristics, such as mild depression or poor sleep, have a pervasive influence on affect. Such characteristics are correlated at least as highly with affect as with satisfaction. (ii) Local features of the current situation, such as the partners in interactions or the level of time pressure in the work situation, exert a powerful influence on affect. (iii) Life circumstances have relatively small effects on affective experience, unless they are locally salient, as

in the case of time pressure at work, or when the individual is intensely preoccupied with a topic, as is most likely to happen for a limited time after a marked change of circumstances. Thus, time pressure is always relevant for affect at work, but job security is affectively important mainly when one thinks about it. Life circumstances are also likely to become salient when people are questioned about their well-being and implicitly encouraged to evaluate how (un)fortunate they are. As a result, circumstances often have more impact on life satisfaction than on affective experience, in accord with the focusing hypothesis.

The present analysis does not suggest that circumstances are irrelevant to well-being. On the contrary, the observation of large variations in affective state during the course of a normal day highlights the importance of optimizing the allocation of time across situations and activities, subject to time and income constraints (30, 31).

The goal of this report was to introduce a new tool for the study of well-being and to illustrate its potential uses. The following features define a generic DRM study: (i) the elicitation of a detailed description of the previous day in the respondent's life; (ii) the goal of approximating the results of continuous, real-time experience measurement; (iii) procedures designed to support accurate retrieval of specific episodes; (iv) structured elicitation of the objective circumstances of episodes; and (v) multidimensional description of the affect experienced in each episode.



**Fig. 3.** Range of mean enjoyment ratings for lowest and highest levels of selected person and job characteristics. Open circles represent the mean for the most enjoyable category of the characteristic, and closed circles for the least enjoyable. Horizontal hash marks show results after controlling for other job features [for (A) to (D)] or for other personal features [for (E) to (H)]. (A) Constant pressure to work quickly (definitely yes/definitely not) work episodes. (B) Constant pressure to work quickly (definitely yes/definitely not) home episodes. (C) At risk of being laid off (definitely yes or definitely not) work episodes. (D) Requires specialized education/training (definitely yes or definitely not) work episodes. (E) Sleep quality (very bad or very good) home episodes. (F) Importance of religion (not at all or very important) home episodes. (G) Household income (less than \$30,000 or more than \$90,000) home episodes. (H) Marital status (divorced or married) home episodes.



Many variations of the method are possible. The activity and affect descriptors used to describe episodes should fit the particular topic of investigation. Interactive questionnaires offer further opportunities to tailor the affect terms to the respective episode; for example, when the individual identifies an episode as an interaction with customers rather than with family members, different descriptors could be presented. Other variations could make the method more practical for adoption in conventional surveys. Our preliminary work suggests that much of the benefit of the DRM in producing accurate emotional recall could be retained if respondents are asked to retrieve specific recent episodes of a designated type (e.g., "the last occasion on which you went out to dinner"). When samples are large and interviewing time is scarce, the allocation of different situations to subgroups of respondents makes it possible to achieve comprehensive coverage of situations while minimizing respondent burden. In conjunction with time-use data obtained from other sources, affect profiles of the main activities in which people engage could be integrated to produce a duration-weighted assessment of the experience of the population and of subgroups. The DRM or its variants could also contribute to the development of an accounting system for the well-being of society, a potentially important tool for social policy (32, 33).

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## Conditional Use of Sex and Parthenogenesis for Worker and Queen Production in Ants

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The near-ubiquity of sexual reproduction in animal species has long been considered a paradox because sexually reproducing individuals transmit only half of their genome to their progeny. Here, we show that the ant *Cataglyphis cursor* circumvents this cost by using alternative modes of reproduction for the production of reproductive and nonreproductive offspring. New queens are almost exclusively produced by parthenogenesis, whereas workers are produced by normal sexual reproduction. By selectively using sex for somatic growth and parthenogenesis for germline production, *C. cursor* has taken advantage of the ant caste system to benefit from the advantages of both sexual and asexual reproduction.

The main advantage of asexual reproduction is that it confers a twofold advantage over sexuality by allowing, generation by generation, the transmission of twice the number of genes to offspring (1, 2). However, asexual reproduction is also associated with both short-term and long-term disadvantages, including a lower genetic diversity of offspring

and a reduced rate of adaptive evolution of species (3, 4). The nature and the degree of the cost associated with asexual reproduction is expected to vary across taxa, depending on the biology of the species and the type of environment in which they live (1–3).

In ants, as in other Hymenoptera, females are usually produced by sexual reproduction and are diploid, whereas males develop from unfertilized eggs and are haploid (3). The diploid fertilized eggs can develop into either new queens (gynes) or workers, with the developmental switch generally under environmental control (5). In the Cape honey bee and five ant species, however, unmated workers may reproduce by thelytokous parthenogenesis (6–11); that is, they may produce female

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